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VARIABILITY OF SEDIMENT AND SALT LOADS IN THE UPPER COLORADO RIVER BASIN: SIGNIFICANCE FOR CONSERVATION AND MANAGEMENT

Phase I

Final Report

to

National Science Foundation
Small Business Innovation Research

submitted by

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APPENDIX D

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I — PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Water Engineering & Technology, Inc. 419 Canyon, Suite 225 Fort Collins, Colorado 80521	SBIR — 1987 Phase I	151-8660788
	4. Award Period From 06/01/87 To 11/30/87	5. Cumulative Award Amount $34,575.00

6. Project Title: Variability of sediment and salt loads in the Colorado River. Significance for conservation and management.

PART II — SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

Several investigators have described a dramatic decrease of suspended-sediment load in the Colorado River in about 1941. The objective of this research was to investigate both sediment and salt loads in the upper Colorado River basin and to determine the reason for any change.

Analysis of sediment and salt load data shows that, although affected by hydrologic variability, both sediment (6 stations) and salt (14 stations) loads have decreased since about 1935. Previous explanations that the decrease was a result of changed sampling procedures, climatic fluctuations and land-use changes can be discounted.

Aerial reconnaissance, and field surveys show that the incised channels (arroyos), that once supplied large quantities of sediment to the Colorado River, during the period starting about 1880, have widened. In addition new flood plains have formed. Decreased sediment production from upstream tributaries and from the channel side walls, and sediment storage in the flood plains, all appear to be the reason for the significant regional reduction of sediment loads. Reduced erosion and sediment storage also may account for the reduced salt loads.

These findings have significant implications for land management in the semiarid regions of southwestern United States. More attention needs to be given to the stabilization of the stored sediments, which in the event of a further erosional episode may return sediment and salt loads to undesirable high values, which may adversely affect downstream agriculture as well as bridges and other riverine structures. i.e. riparian mgt.

Key Words to Identify Research or Technology (8 maximum)

Sediment loads, salt loads, salinity, and incised channels.

PART III — TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations	X				
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date

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FIGURES (continued)

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47% natural sources

37% irrigation

12% reservoir evaporation

3% water exports

1% municipal and industrial use

Blackman et al. (1973) estimate that 84% of the natural sources of salinity within the upper Colorado River basin are due to diffuse sources, the erosion of saline soils and marine shales. This erosion is also the source of the high sediment loads transported by the Colorado River, which have a significant effect on reservoir life, water quality, other engineering structures, and channel stability.

In the late 19th century and early 20th century many valleys in the Colorado River basin were incised as arroyos and gullies developed (Fig. 1). These incised channels (Schumm, et al., 1984) delivered vast amounts of sediment to the Colorado River. However in the 1940's there was remarkable apparent change in this situation. Between 1941 and 1944 there was a decrease in sediment load through the Grand Canyon that, depending upon runoff, ranged from fifty to one hundred and seventy million tons per year (Fig. 2). If this change had been in the other direction, the response of the scientific and environmental community would have been immediate shock. However, the decrease was less alarming, and it has not been thoroughly investigated, both because it is difficult to explain, and the explanation probably requires study of the entire upper Colorado River basin.

Associated with the decrease of sediment load was a decrease of salt load (Fig. 3). The concentration of dissolved-solids at Imperial Dam,

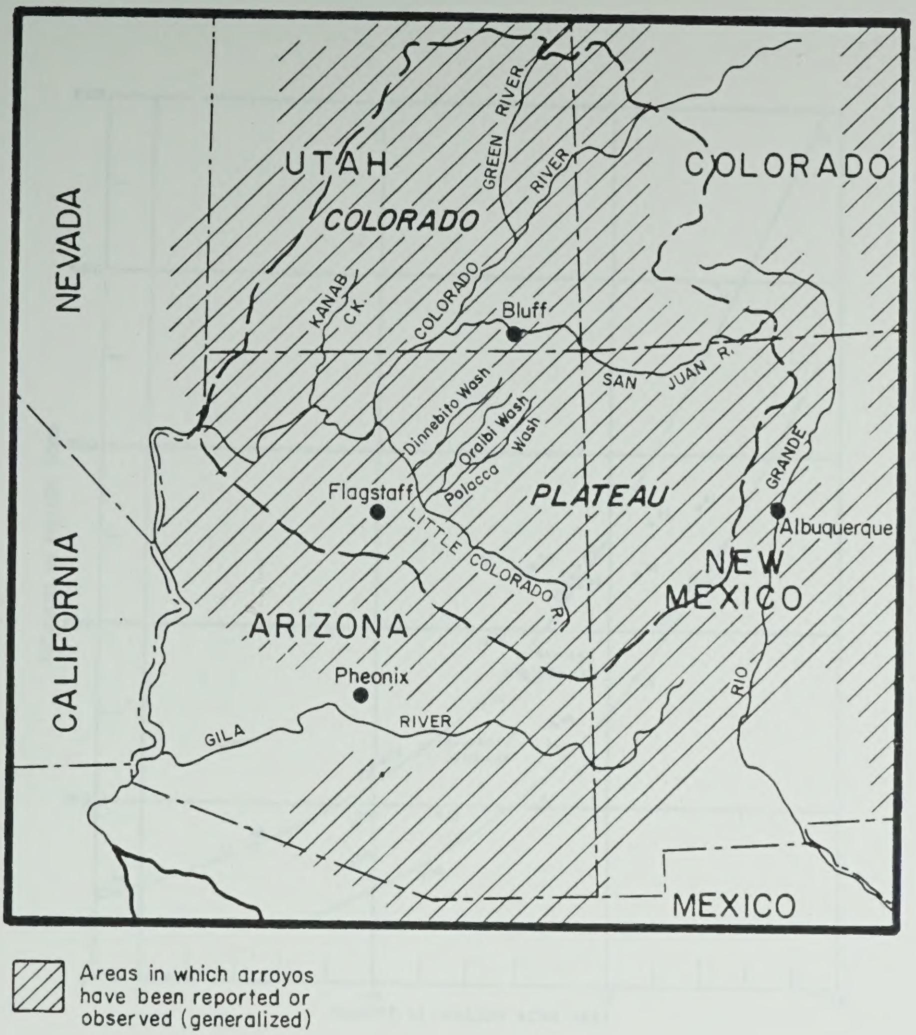

Figure 1 Map of the Southwest showing boundary of Colorado Plateau physiographic province (dashed line) and main areas affected by arroyo entrenchment.

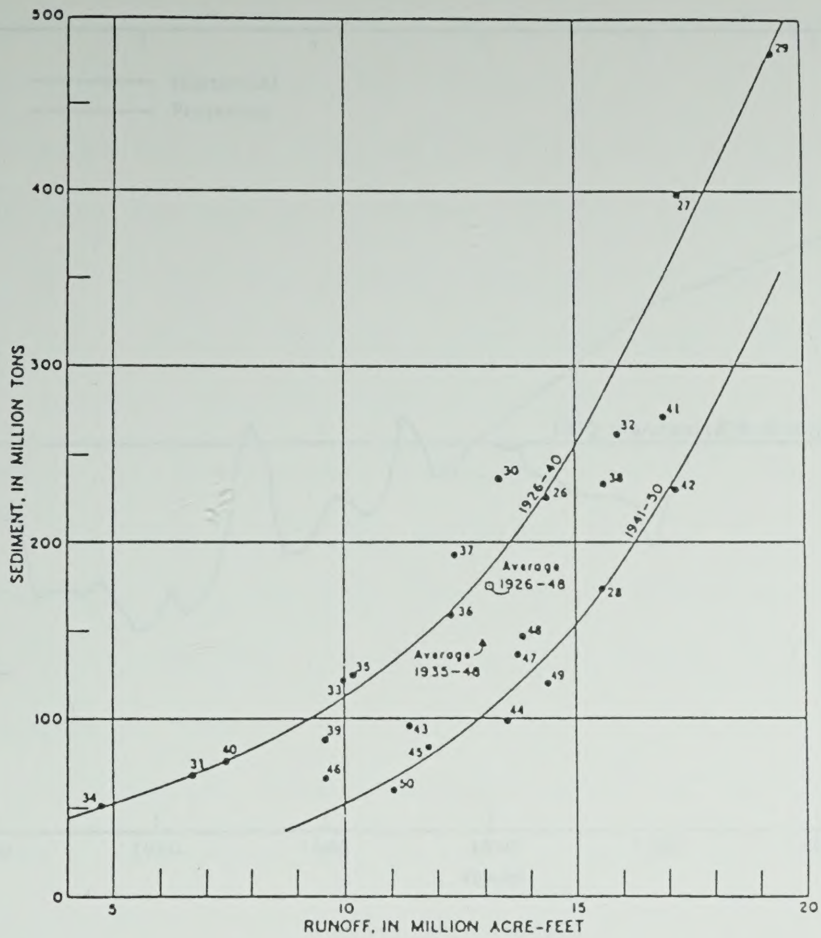

Figure 2 Relation between annual runoff and suspended-sediment load of the Colorado River at Grand Canyon, 1926 to 1957 (from Thomas et al., 1963).

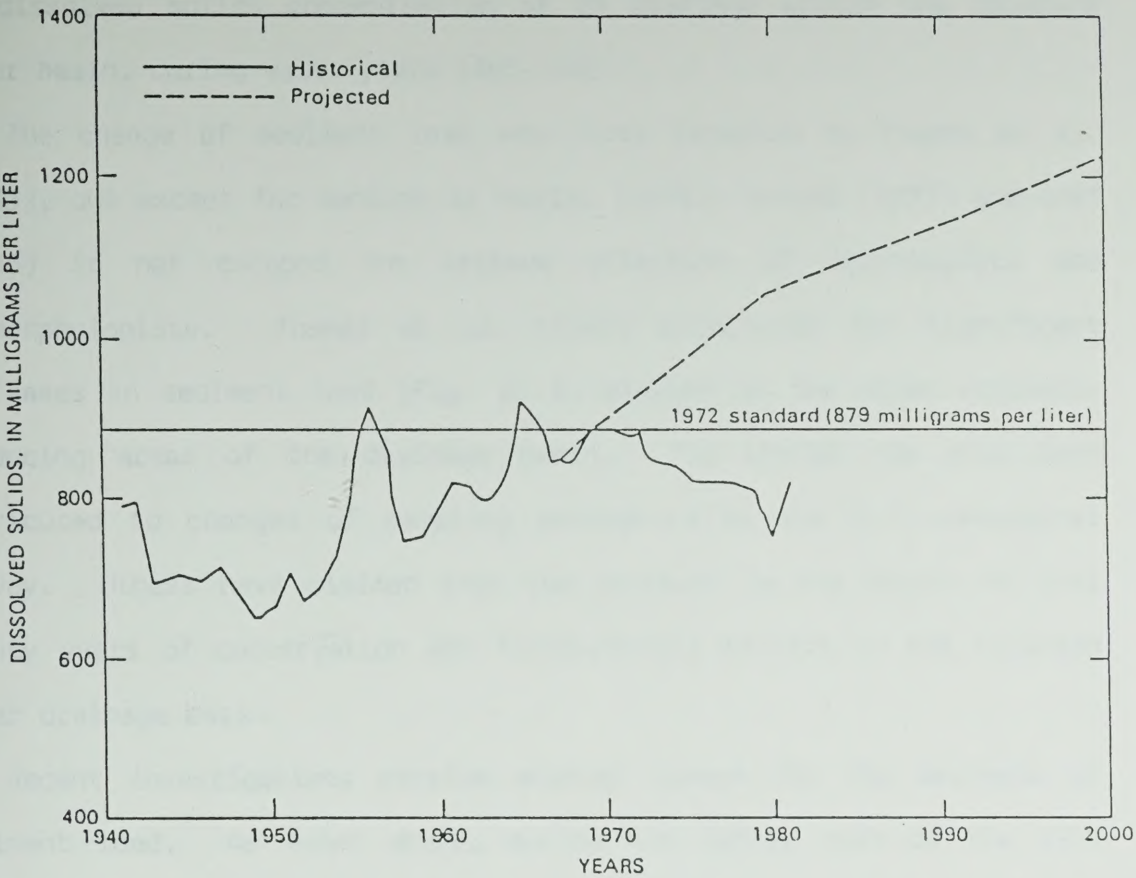

Figure 3 Historical versus projected dissolved solids at Imperial Dam, Arizona without salinity control (from Mueller and Moody, 1983).

Arizona, decreased significantly during the period 1940 to 1950 and from 1965 to 1980, but it increased between 1950 and 1965. The decrease between 1940 and 1950 (Fig. 3) correlates with the decrease in sediment discharge at Grand Canyon (Fig. 2). Kircher (1984) reports a decrease in dissolved solids concentration at 20 stations within the Colorado River basin, during water years 1965-1983.

The change of sediment load was first reported by Thomas et al. (1963), but except for mention by Hadley (1974), Schumm (1977) and Graf (1985) it has escaped the serious attention of hydrologists and geomorphologists. Thomas et al. (1963) attributed the significant decreases in sediment load (Fig. 2) to drought in the major sediment-producing areas of the drainage basin. The change has also been attributed to changes of sampling procedures by the U.S. Geological Survey. Others have claimed that the decrease is the result of over twenty years of conservation and flood-control efforts in the Colorado River drainage basin.

Recent investigations provide another reason for the decrease of sediment load. As noted above, during the latter part of the 19th century many arroyos formed, and channels incised throughout the Colorado Plateau. Vast quantities of sediment were delivered to the Colorado River via tributaries such as Escalante River, Kanab Cr., and Little Colorado River. However, experimental studies, (Schumm et al., 1987), as well as field studies (Schumm, 1977) indicate that following a major period of sediment production there will be a steady decrease of sediment loads as the incised channels widen and become less efficient

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Recent investigations provide another reason for the decrease of sediment load. As noted above, during the latter part of the 19th century many arroyos formed, and channels incised throughout the Colorado Plateau. Vast quantities of sediment were delivered to the Colorado River via tributaries such as the Paria River, Puerco River, and Little Colorado River. However, experimental studies (Schumm et al., 1987), as well as field studies (Graf, 1983) indicate that following a major period of sediment production there will be a steady decrease in sediment loads as the incised channels widen and become less efficient

transporters of sediments and as the incised channels begin storing sediment in floodplains that develop in the lower reaches of the entrenched valley (Harvey et al., 1985).

Objectives

Obviously plans for future land management and erosion control in the upper Colorado River basin depend upon which interpretation of sediment and salt load change is accepted. If there was an abrupt change of sediment load then upland erosion-control work should be continued. If there is a progressive decrease in sediment load then sediment-control efforts should also be directed toward channel and floodplain stability because in semiarid and arid regions remobilization of the stored sediment by renewed channel incision and widening is likely to produce a return to high levels of sediment and salt loads in the Colorado River.

If the cause of the decrease of sediment and salt load could be determined it would provide a basis for evaluation of many sediment control and salt-control techniques that have been proposed or that are in effect. The result will be a more effective use of conservation funds and the prevention of a return to high sediment and salt loads. Whatever the cause, the change seems to offer an opportunity to investigate the natural as well as man-induced changes of a major river system. Therefore, the objectives of this study are 1) to determine the nature of the sediment and salinity change during the period of record, 2) to explain the changes, and 3) to determine how the results will

affect land management and especially erosion control measures in the Colorado River basin.

Procedure

In this Phase I effort, several arroyos of the Navajo Country, Arizona were selected for field studies as follows: Dinnebito Wash, Oraibi Wash, Polacca Wash and the Rio Puerco tributary of the Little Colorado River (Fig. 1). These arroyos incised at the turn of the century (Thornthwaite et al., 1942), and therefore, changes in channel morphology following the incision can be examined. A literature review was made in order to investigate the causes of and timing of arroyo incision.

An aerial reconnaissance was carried out in order to identify sites for field studies and to determine the areal extent of incised channel adjustment in the region (Fig. 1). In order to investigate the nature of channel adjustment to incision, 47 cross sections of arroyos were surveyed and photographed. It was anticipated that the cross sections from the mouth to the headwaters of an arroyo would reveal the morphological changes that occur during arroyo evolution.

A historical analysis was undertaken to determine channel changes through time. This included a search at the U.S. Geological Survey Photographic Library, Denver, Colorado, that was intended to retrieve historic photographs of arroyos in the Southwest. Aerial photographs of the Navajo Country were obtained through the U.S. Geological Survey National Cartographic Information Center, Denver, Colorado. Recent

photographs were taken at the same locations as the historic photographs, in order to determine the extent of channel change at these locations.

Suspended-sediment, discharge, and dissolved-solids data were collected from various federal agencies for streams in the Colorado River basin in order to discern trends in water quality and quantity. Data were obtained from the U.S. Geological Survey's hydrologic database, WATSTORE, in Reston, Virginia.

2) SEDIMENT AND SALT LOADS

A major part of the Phase I effort was to assemble data on sediment and salt loads in the upper Colorado River basin. This was done in order to determine the nature, magnitude, and timing of changes in salt and suspended-sediment loads.

As noted above, several investigators concluded that sediment loads decreased dramatically in about 1940, (Thomas, 1963; Hadley, 1974; Thompson, 1982, 1984a, 1984b) and data from six of eight sediment sampling stations show a decrease of suspended-sediment loads (tons/day).

Mueller and Moody (1983), Moody and Mueller (1984); and Kircher (1984), report decreases in the dissolved solid loads (tons/year) of the Colorado River basin, and data from 14 of the 20 sampling stations investigated during this study show a decrease of salt load.

Suspended-sediment Load

Suspended-sediment is the sediment that at any given time is maintained in suspension by the upward components of turbulent currents or that exists in suspension as a colloid (Ugland et al., 1985). Suspended-sediment loads and water discharge data, were retrieved from the U.S. Geological Survey hydrologic database, WATSTORE (Hutchinson, 1975). Suspended-sediment loads, that were expressed in tons per year for each water year, were obtained for eight sampling stations (Fig. 4). This annual value was subsequently divided by 365, in order to obtain mean tons per day for each water year. The same procedure was applied

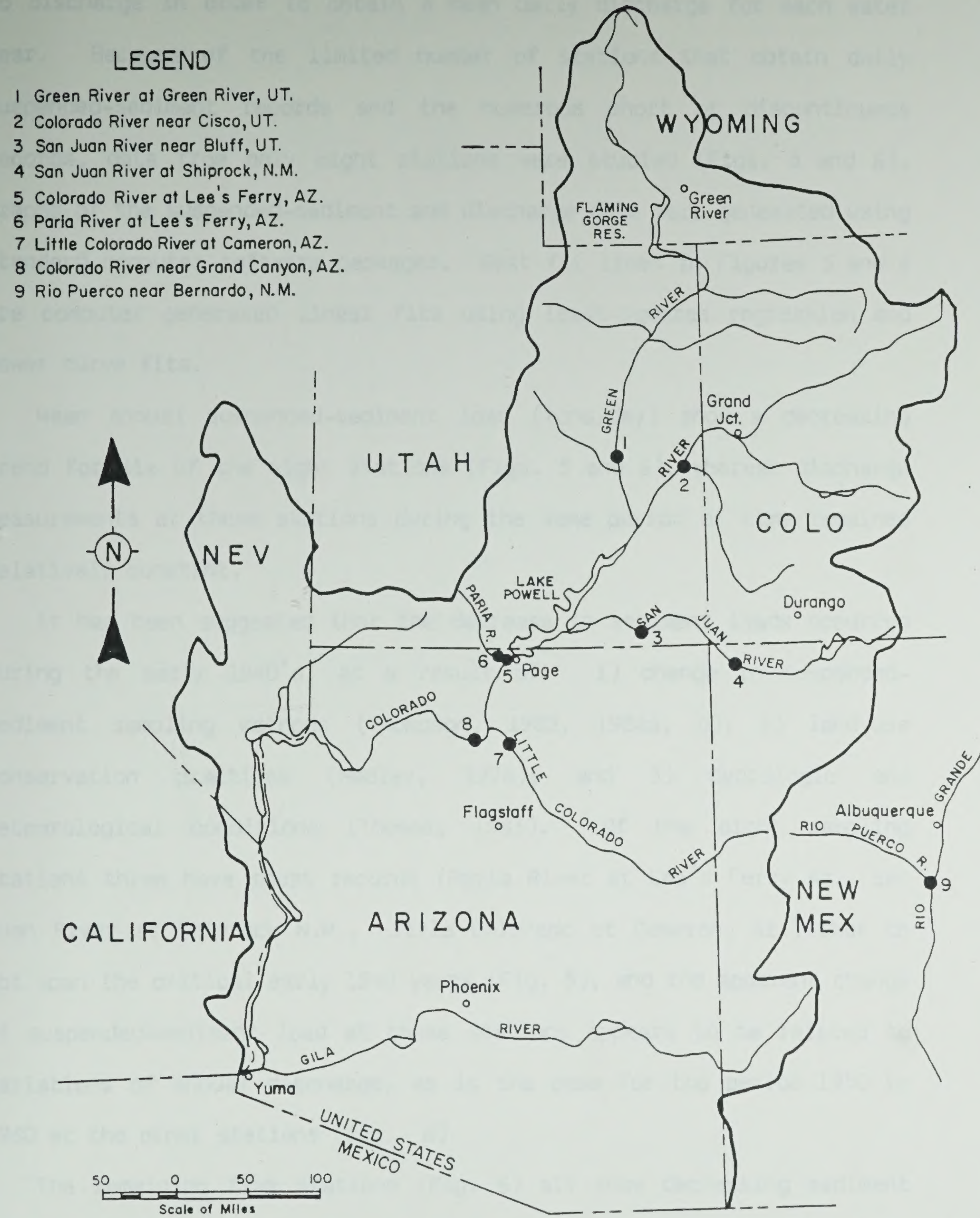


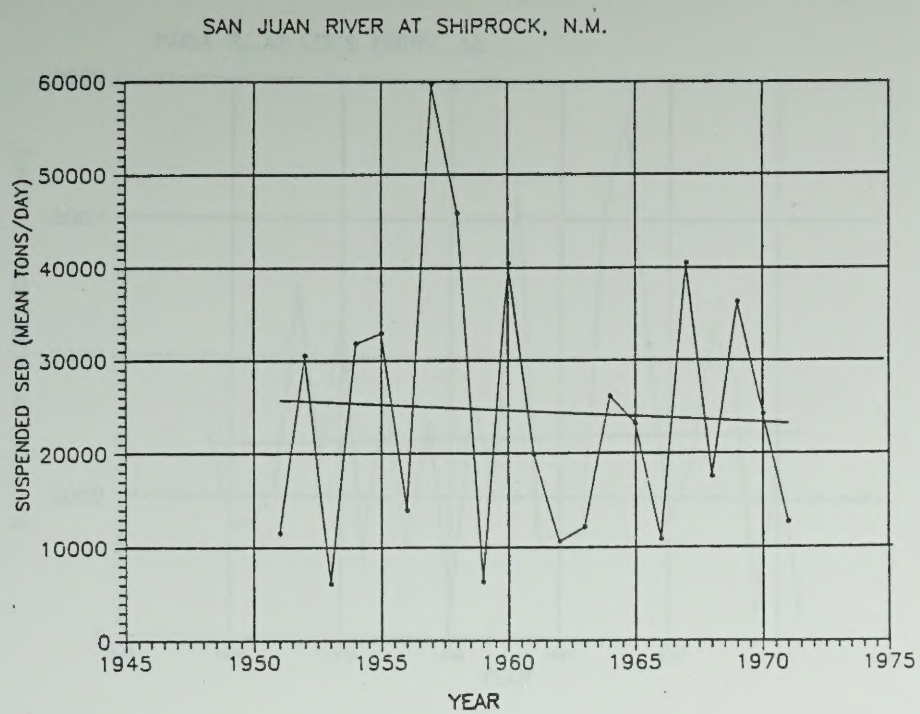
Figure 4 Map showing location of selected suspended-sediment and discharge monitoring stations.

to discharge in order to obtain a mean daily discharge for each water year. Because of the limited number of stations that obtain daily suspended-sediment records and the numerous short or discontinuous records, data from only eight stations were studied (Figs. 5 and 6). Graphs of the suspended-sediment and discharge data were generated using standard computer software packages. Best fit lines in Figures 5 and 6 are computer generated linear fits using least-squares regression and power curve fits.

Mean annual suspended-sediment load (tons/day) show a decreasing trend for six of the eight stations (Figs. 5 and 6), whereas discharge measurements at these stations during the same period of time remained relatively constant.

It has been suggested that the decrease in sediment loads occurred during the early 1940's, as a result of: 1) change in suspended-sediment sampling methods (Thompson, 1982, 1984a, b); 2) land-use conservation practices (Hadley, 1974); and 3) hydrologic and meteorological conditions (Thomas, 1963). Of the eight sampling stations three have short records (Paria River at Lee's Ferry Az., San Juan River at Shiprock N.M., Little Colorado at Cameron, Az.) that do not span the critical early 1940 years (Fig. 5), and the apparent change of suspended-sediment load at these stations appears to be related to variations of annual discharge, as is the case for the period 1950 to 1960 at the other stations (Fig. 6).

The remaining five stations (Fig. 6) all show decreasing sediment loads with little change of mean discharge. The high sediment loads in



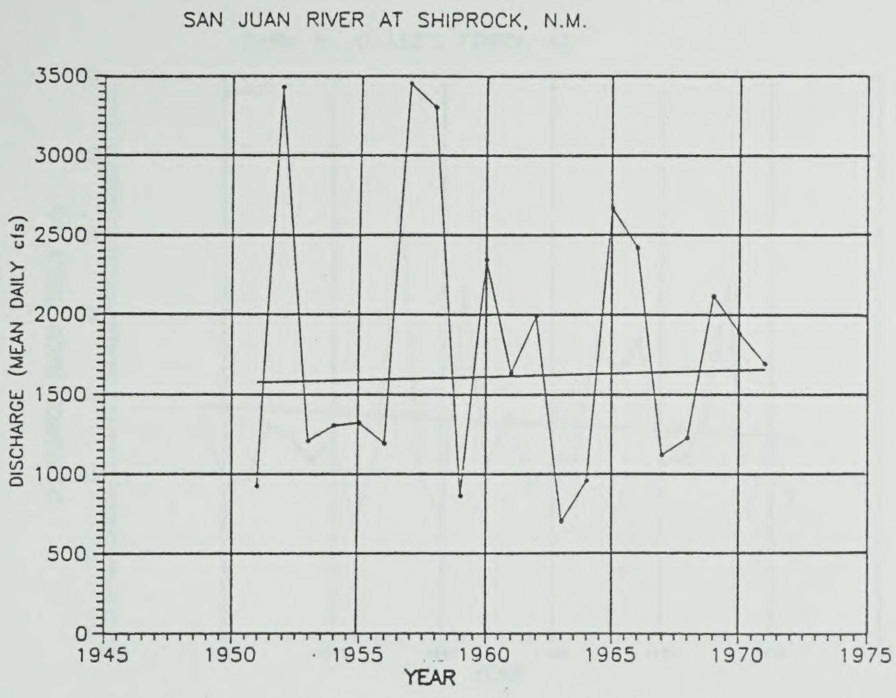
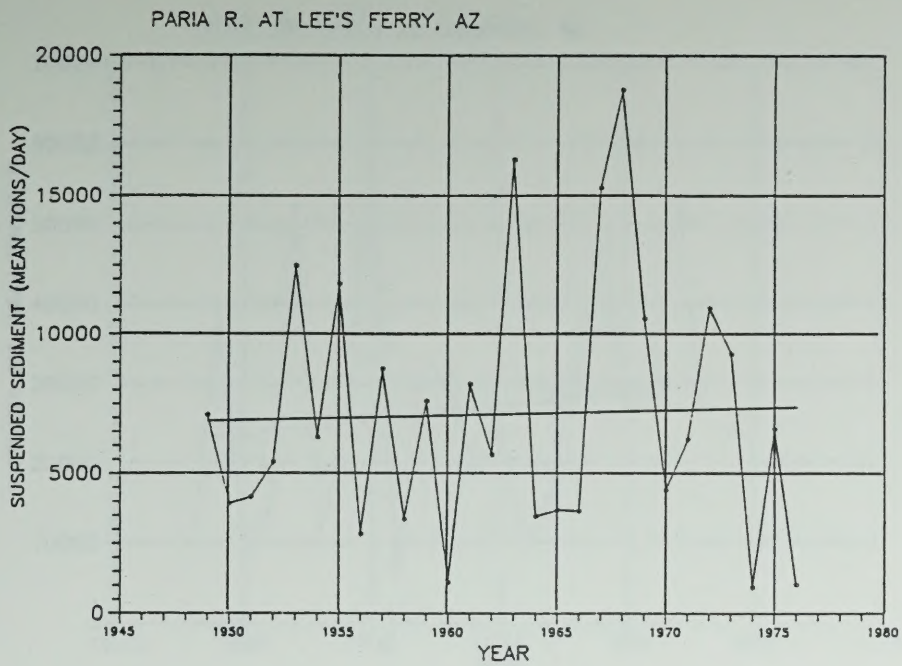
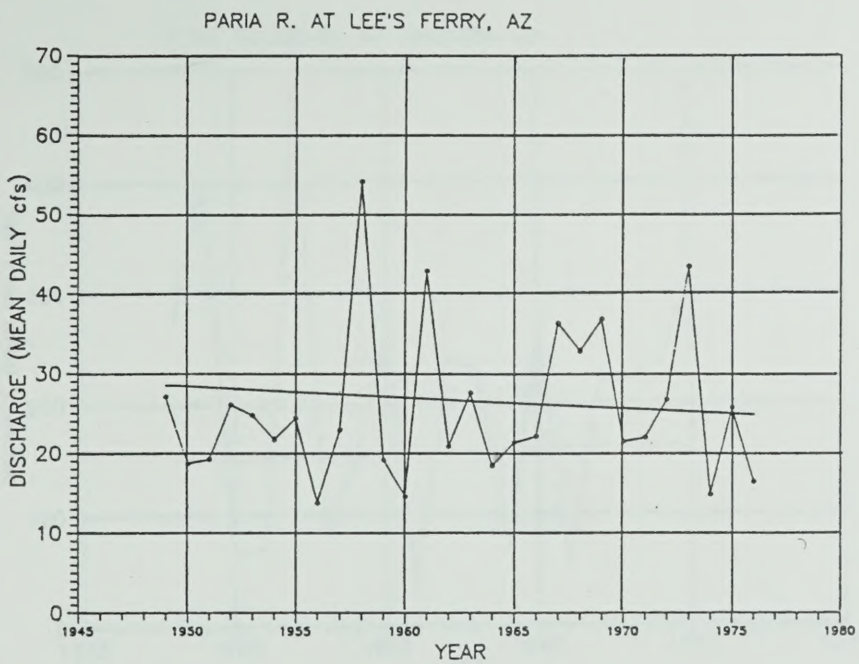


Figure 5 Suspended-sediment loads and discharge with time for stations in the Colorado Plateau with records starting after 1945.





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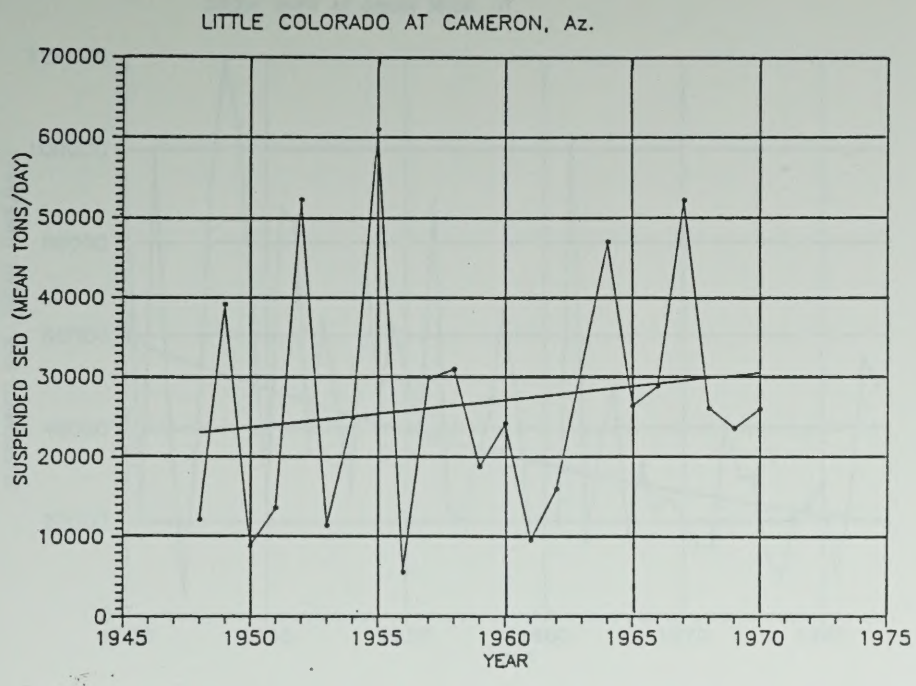

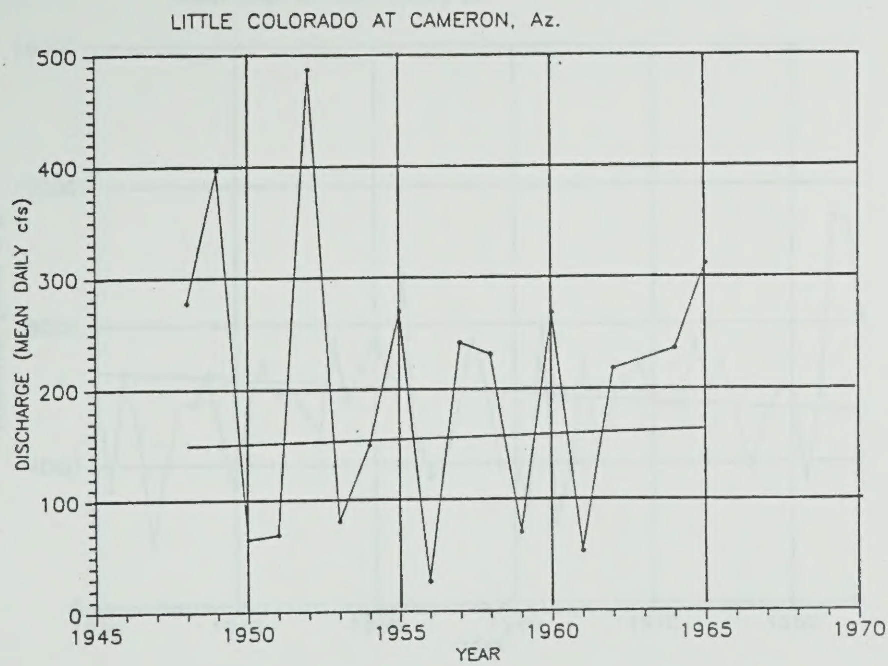

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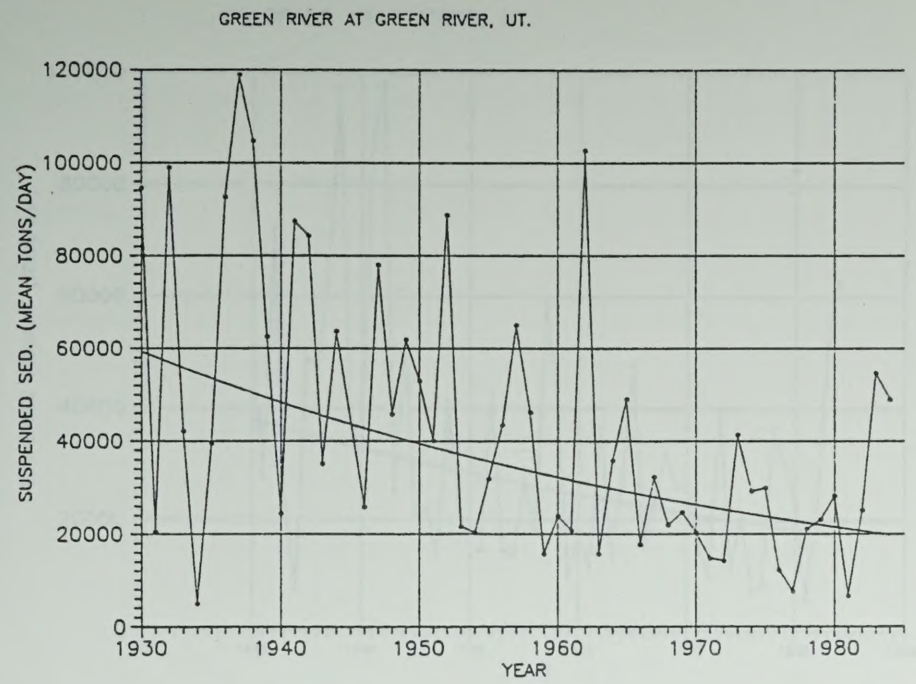


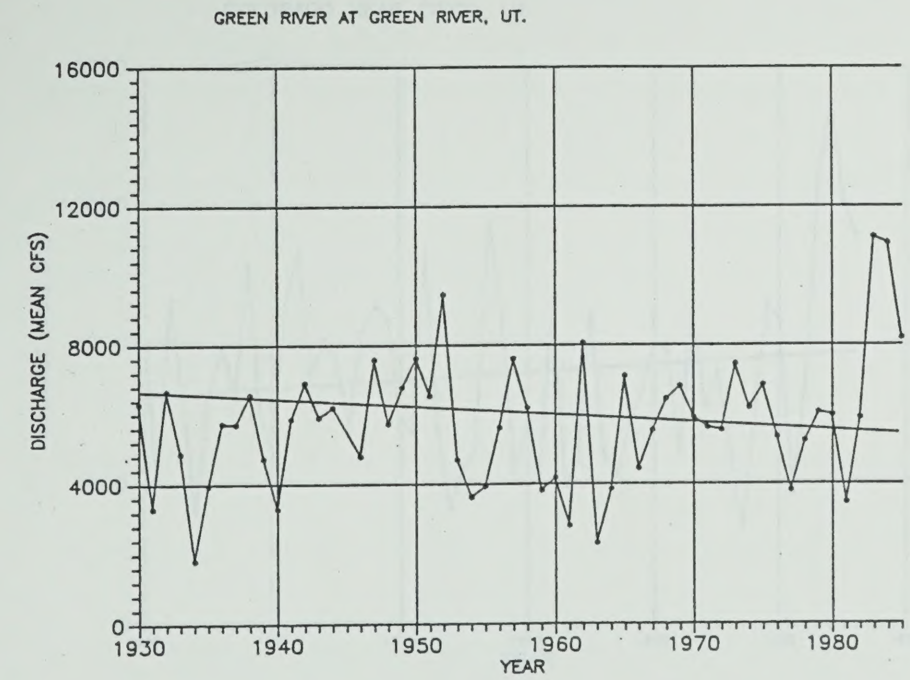
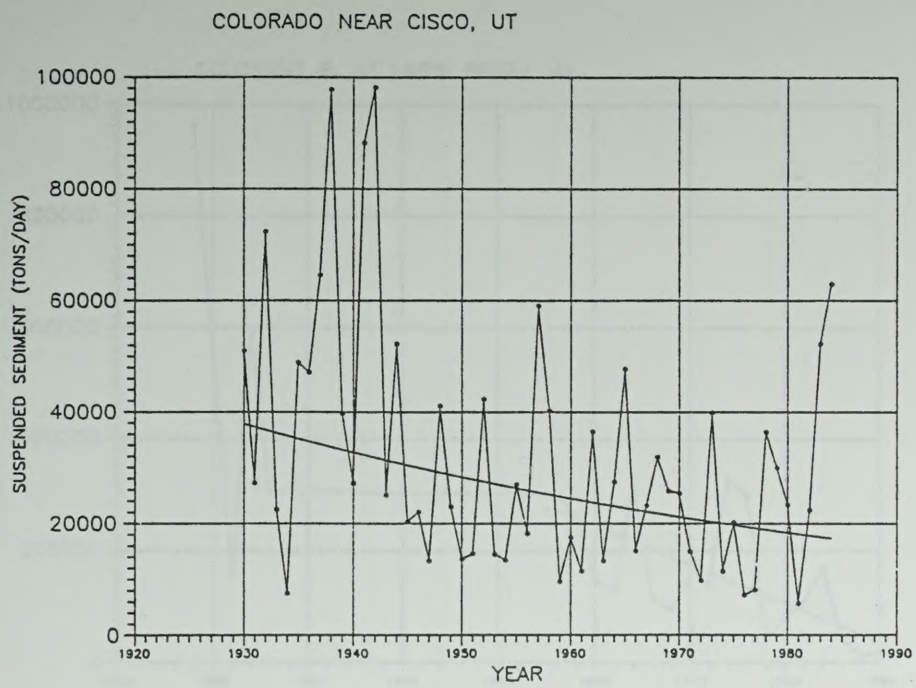
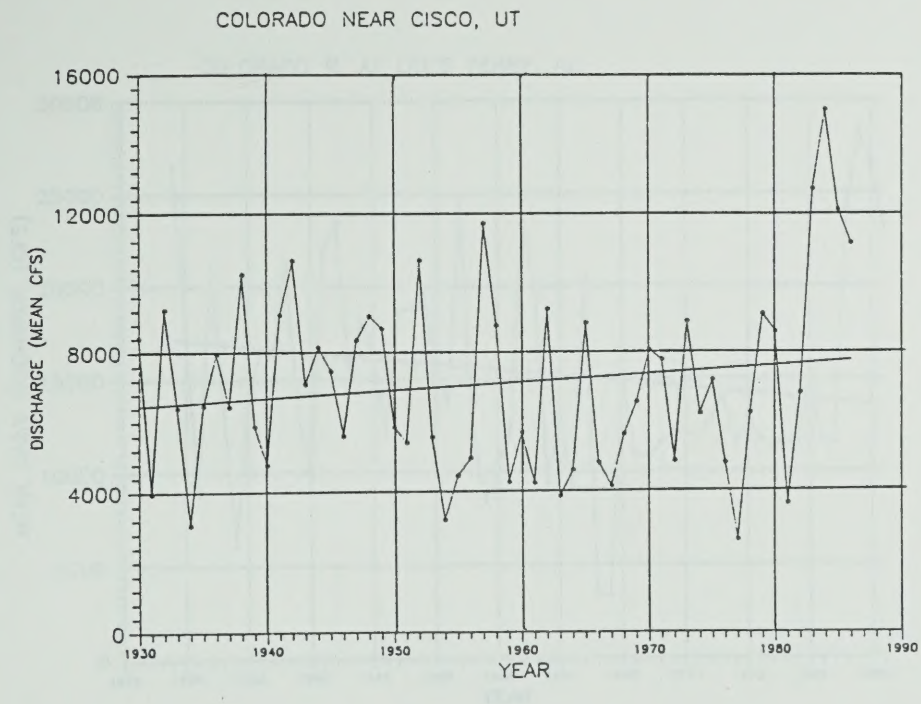


Figure 6 Suspended-sediment loads and discharge with time for stations in the Colorado Plateau with records starting before 1940.





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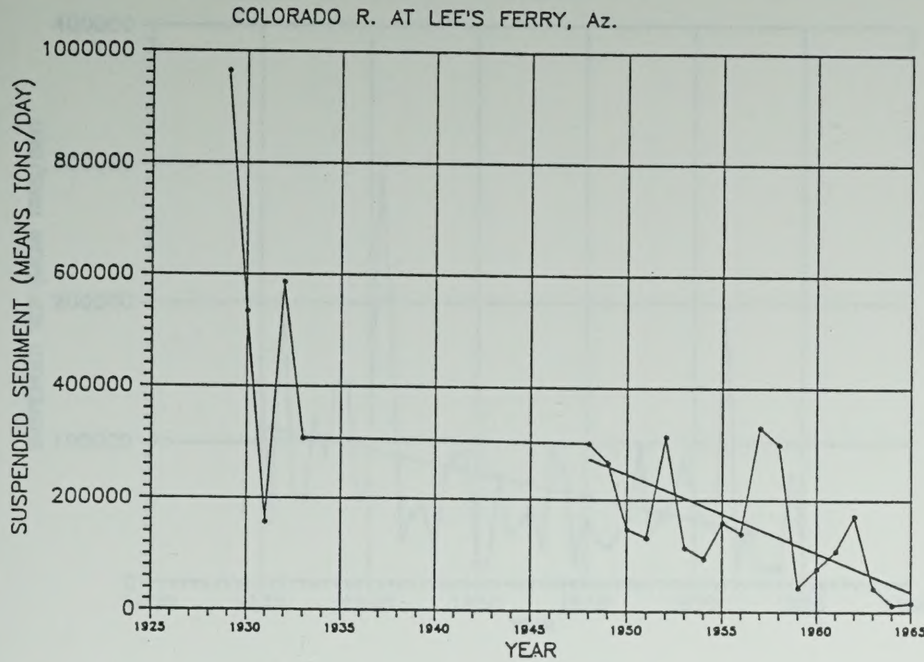

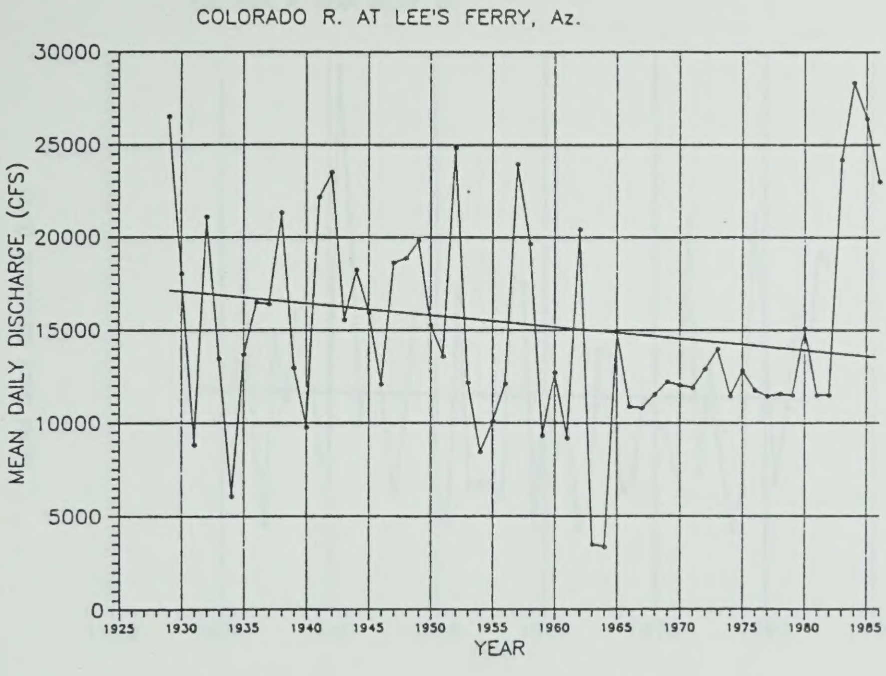

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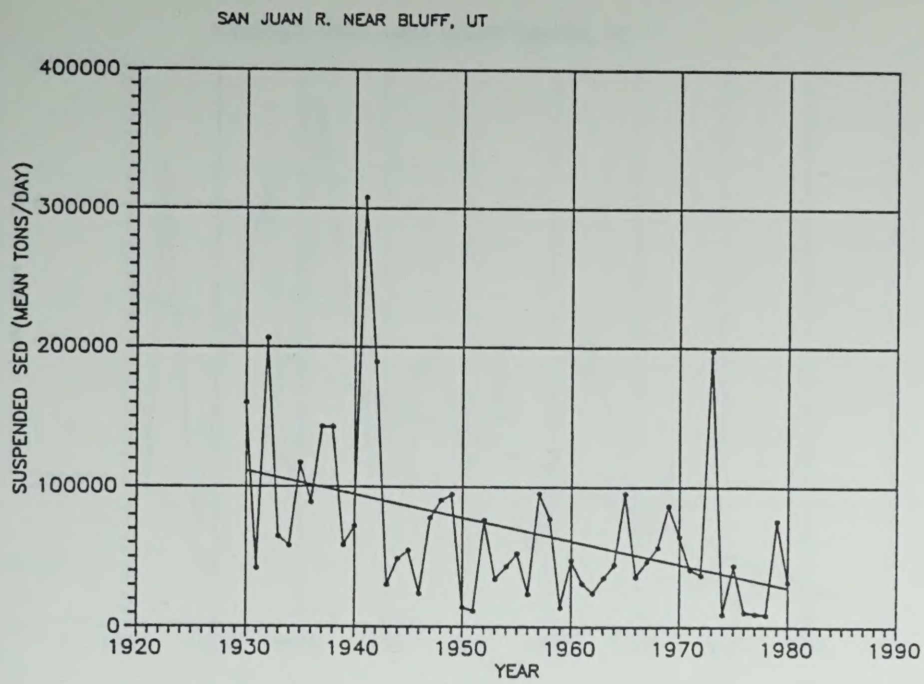

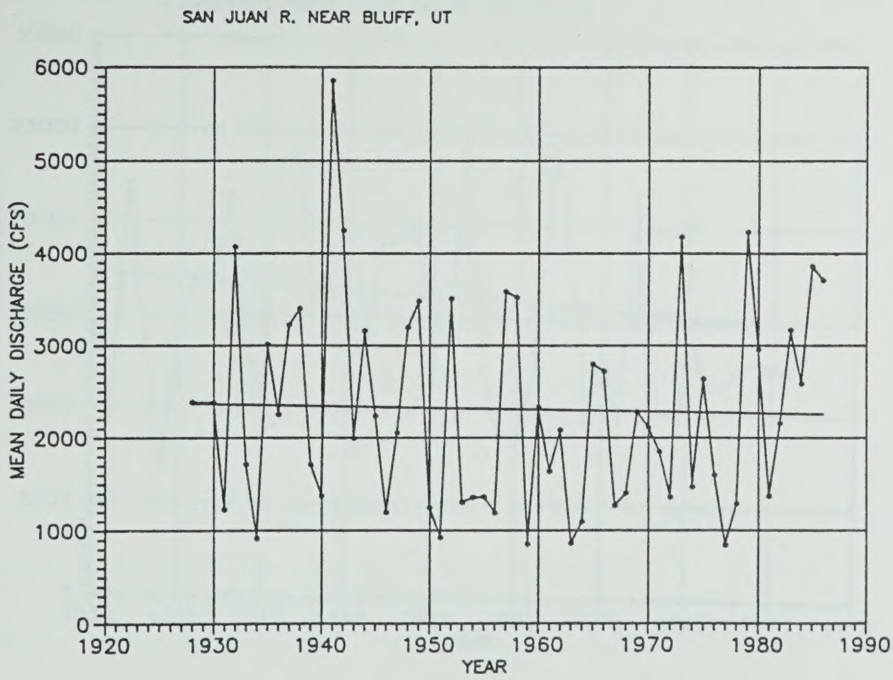

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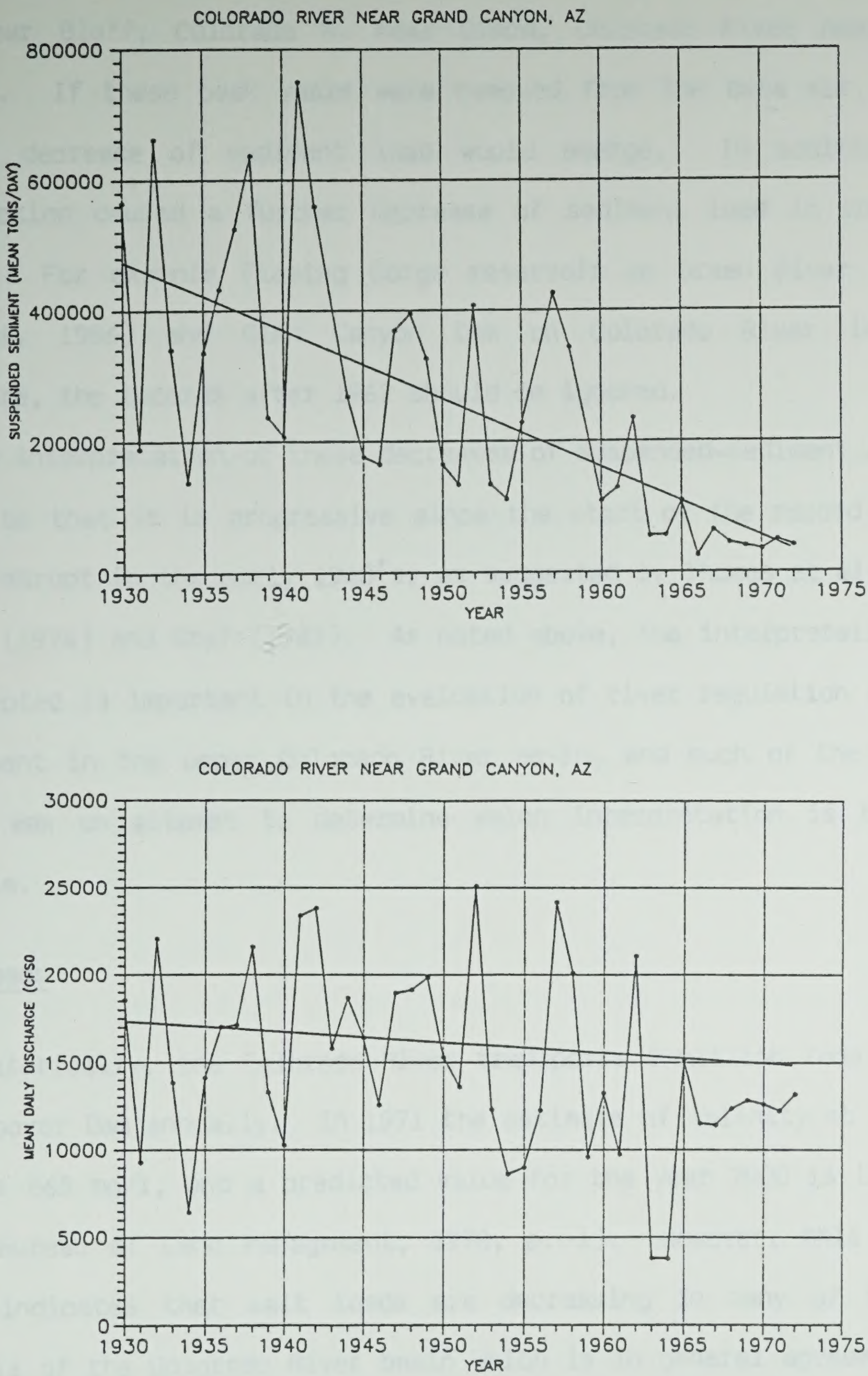

Figure 6 Continued.

1941 and 1942 appear to be related to years of high mean discharge (San Juan near Bluff; Colorado R. near Cisco, Colorado River near Grand Canyon). If these peak years were removed from the data set, a more orderly decrease of sediment load would emerge. In addition, dam construction caused a further decrease of sediment load in the early 1960's. For example Flaming Gorge reservoir on Green River in 1962 (Andrews, 1986) and Glen Canyon Dam on Colorado River in 1963. Therefore, the records after 1962 should be ignored.

The interpretation of these decreases of suspended-sediment load can either be that it is progressive since the start of the record or that it was abrupt in the early 1940's; as suggested by Thomas et al. (1963) Hadley (1974) and Graf (1985). As noted above, the interpretation that is accepted is important in the evaluation of river regulation and land management in the upper Colorado River basin, and much of the Phase I effort was an attempt to determine which interpretation is the most probable.

<u>Salt Loads</u>

Historically, the Colorado River transports 9 million tons of salt past Hoover Dam annually. In 1971 the estimate of salinity at Imperial Dam was 865 mg/l, and a predicted value for the year 2000 is 1340 mg/l (U.S. Bureau of Land Management, 1978, p. 1). However, this Phase I study indicates that salt loads are decreasing in many of the main channels of the Colorado River basin which is in general agreement with the findings of Mueller and Moody (1983) and Kircher (1984).

Natural sources of salts are point sources and diffuse sources. Natural point sources include springs and artesian aquifers, which contribute as much as 500,000 tons annually (U.S. Bureau of Land Management, 1978, p. 22). Diffuse sources of salts are marine shale outcrops (Schumm and Gregory, 1986) and salt efflorescence on alluvial surfaces (Bhasker, et al., 1981). Geologic formations that contribute significant amounts of salt loads to drainages in the Colorado Plateau, are the Mancos Shale (Fig. 7) and the Lewis Shale.

Dissolved-solids are the sum of the individual dissolved ionic constituents present in water, and these are a measure of the salinity of water. Dissolved-solid data for a given stream flow-gaging station are collected at infrequent intervals, however specific conductance and discharge may be measured by automatic monitoring equipment. Specific conductance is a measure of the ability of water to conduct an electrical current, and it can be used as an estimate of the salinity or dissolved-solids content of the water (Lieberman et al., 1987).

Salinity data used in this report was obtained from the Department of Interior (1987) for 20 gaging stations in the Colorado River basin. Other data were obtained from Dave Mueller, U.S. Geological Survey, Denver, Colorado, (unpublished data of annual dissolved-solids loads at selected streamflow gaging stations in the upper Colorado River basin). Graphs of the dissolved-solids data were generated using standard computer software packages (Fig. 9). Best fit lines in Figures 9 are computer generated linear fits using least-squares regression.

The data indicate that 14 of 20 stations in the Colorado River basin, have decreasing dissolved solid loads (Figs. 8, 9). These

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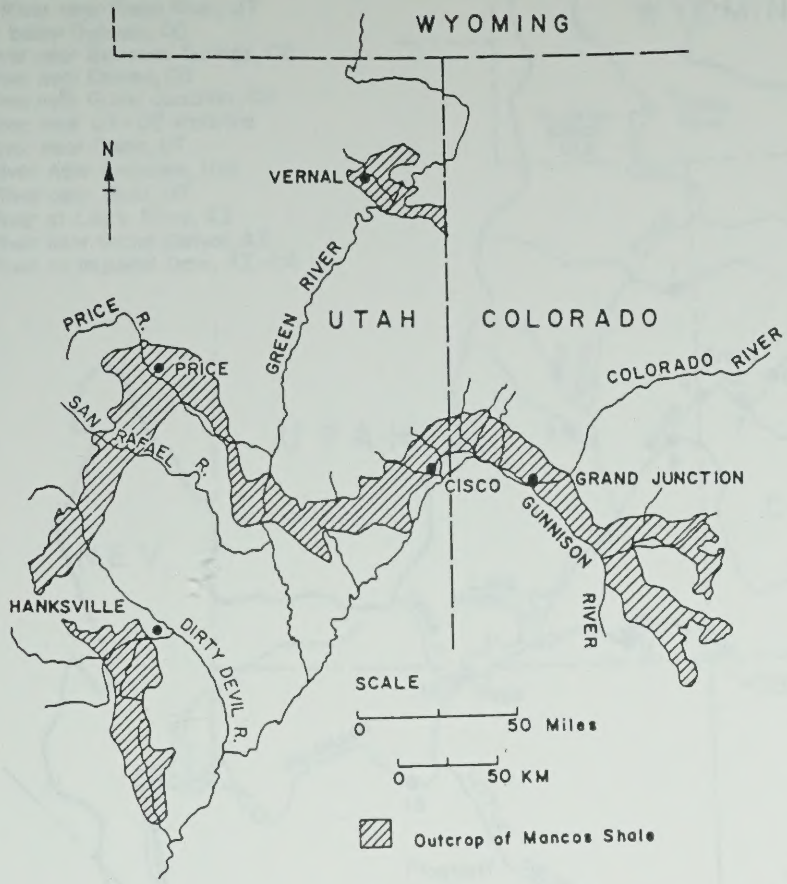


Figure 7 Map indicating outcrops of Mancos Shale along part of the Colorado River (from Williams, 1975).

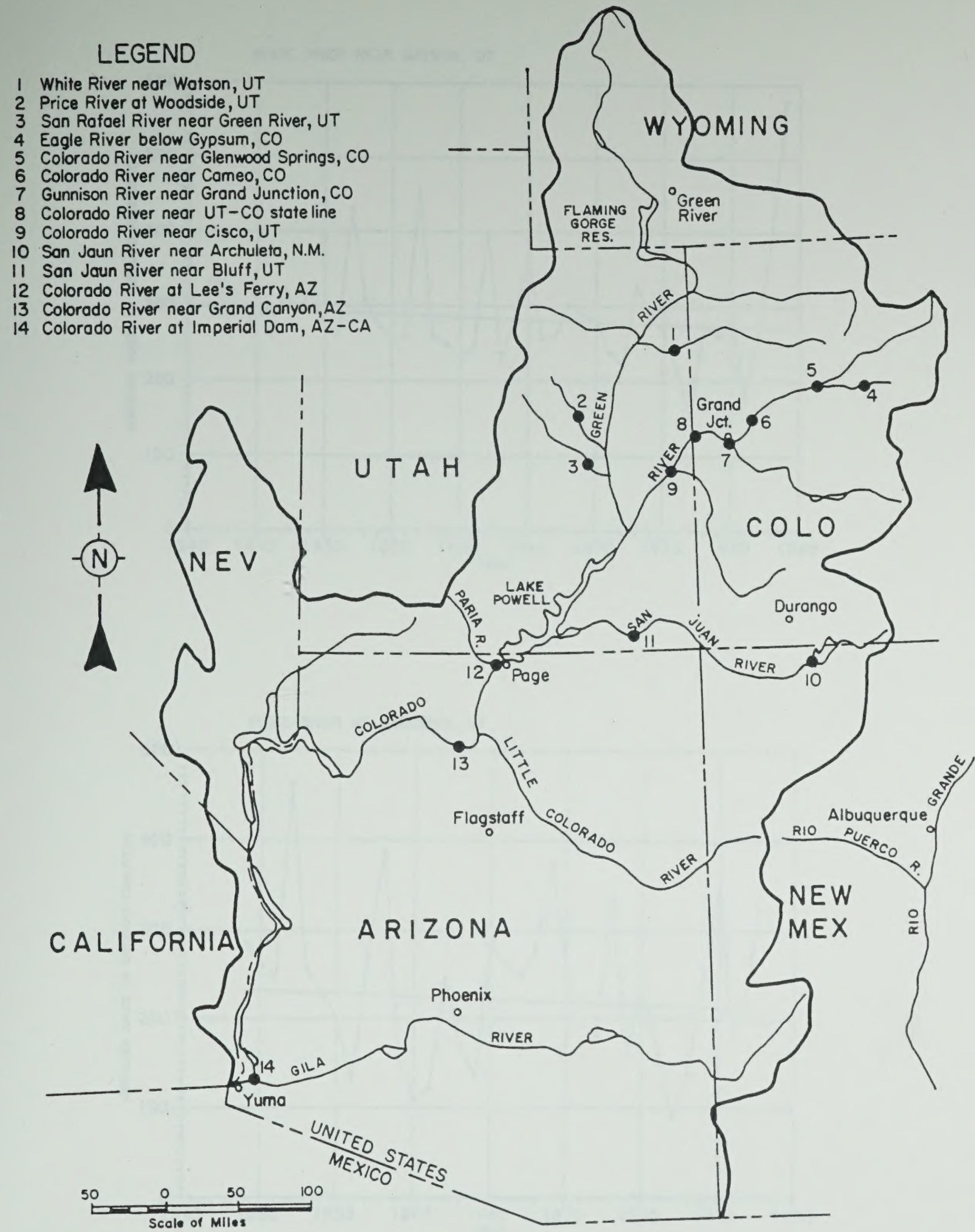
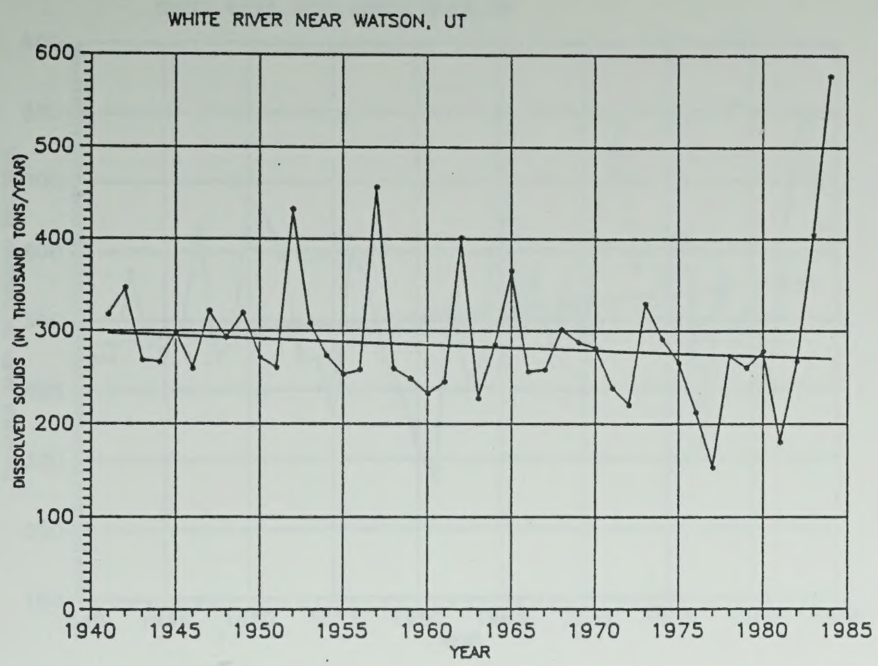


Figure 8 Map showing location of monitoring stations which indicate a decrease in dissolved-solids load.



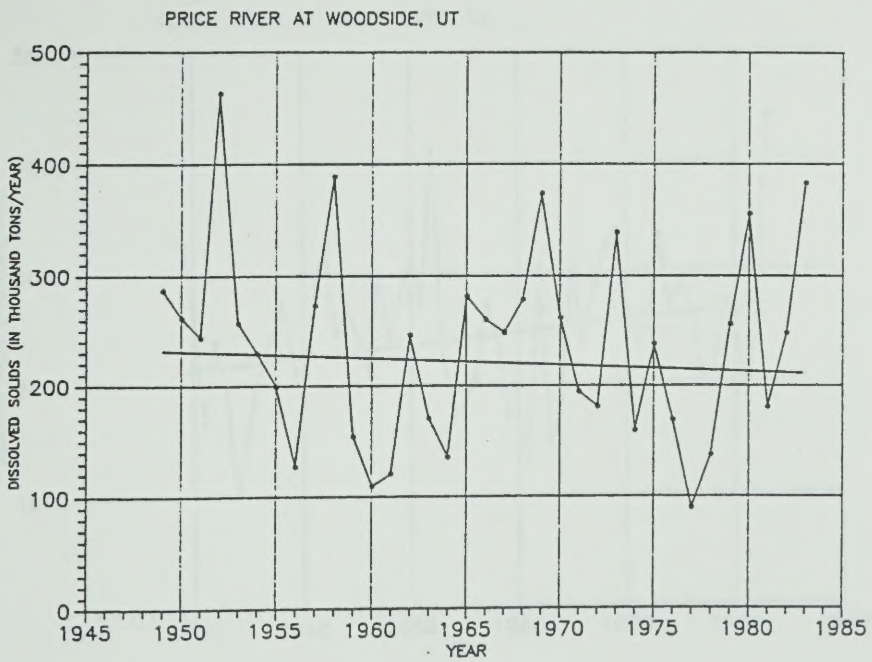
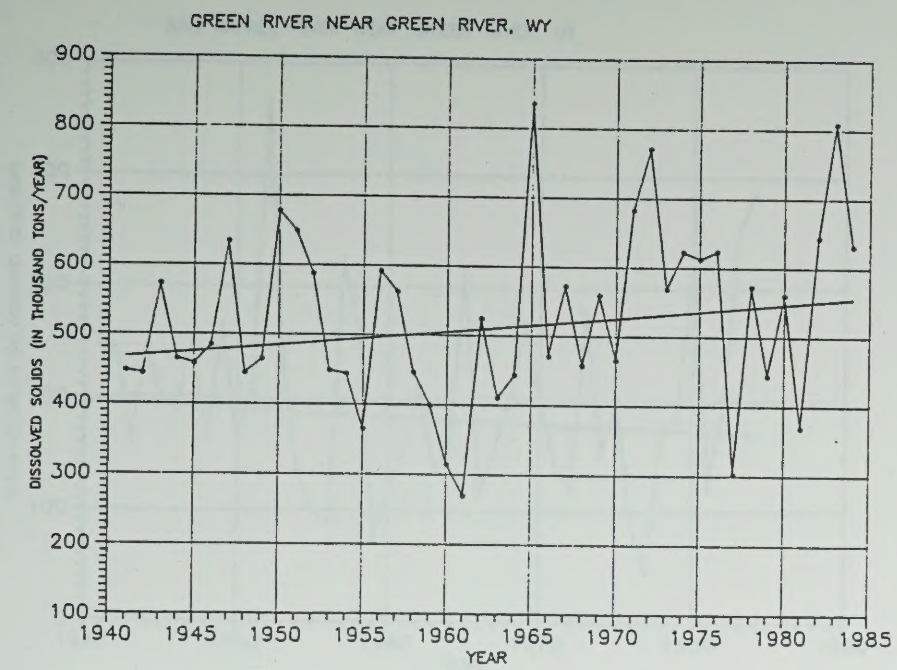
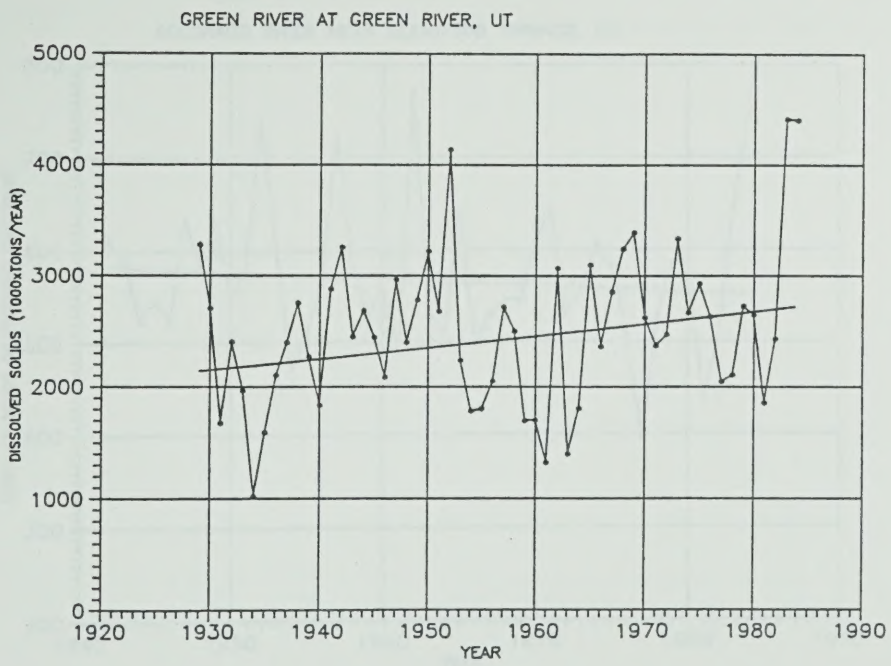


Figure 9 Dissolved-solids load with time for stations in the Colorado River Basin.





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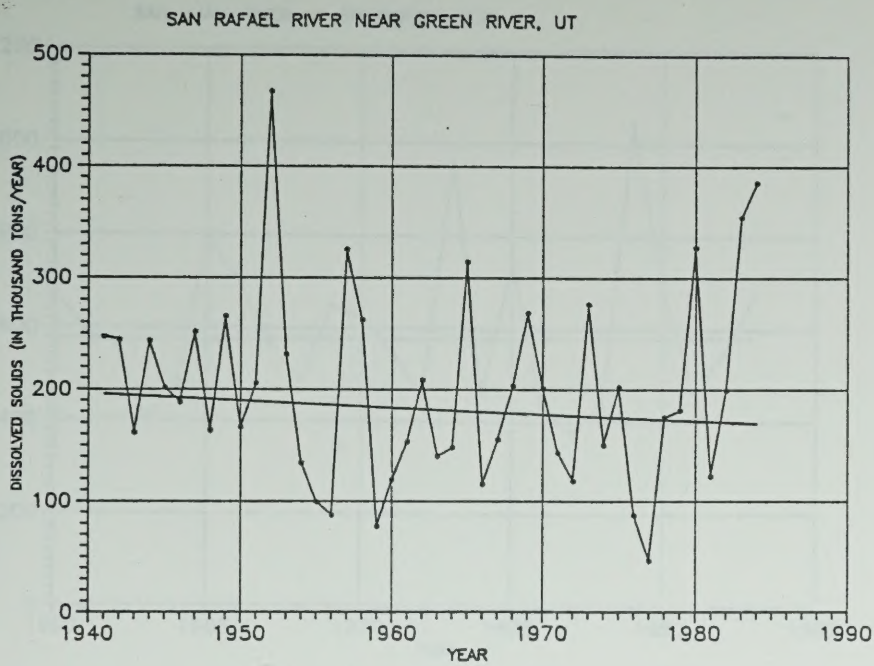

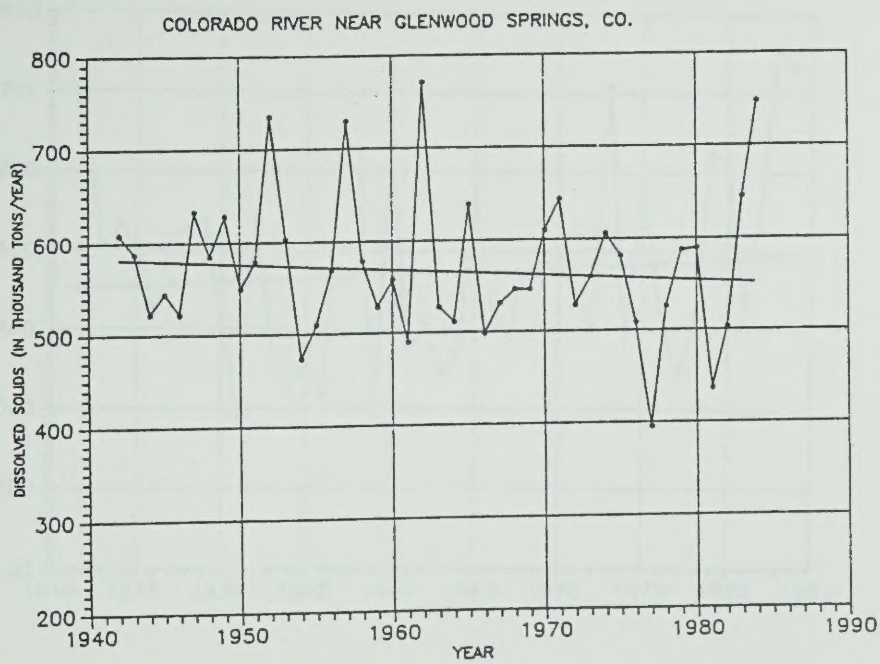

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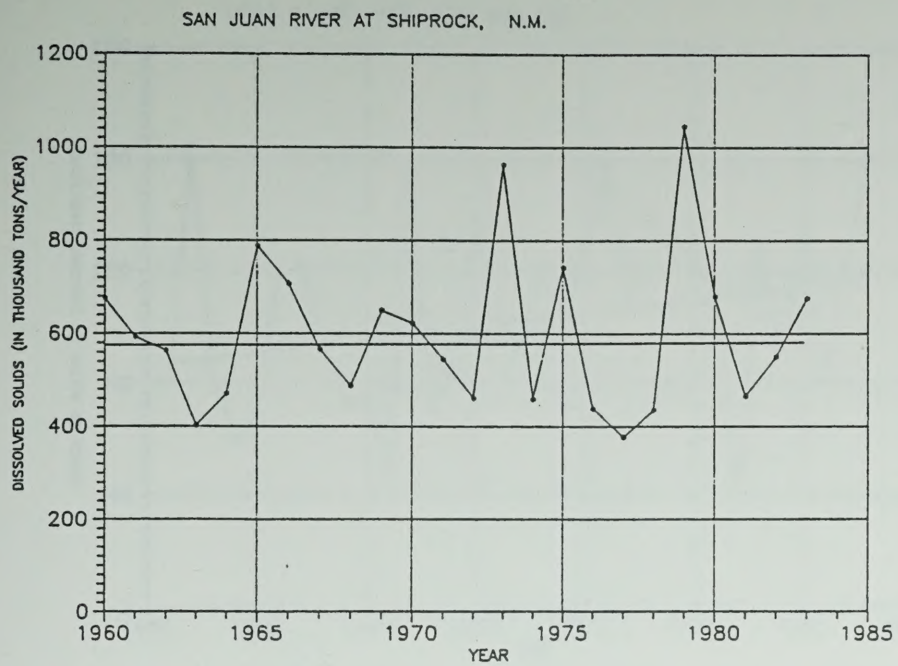

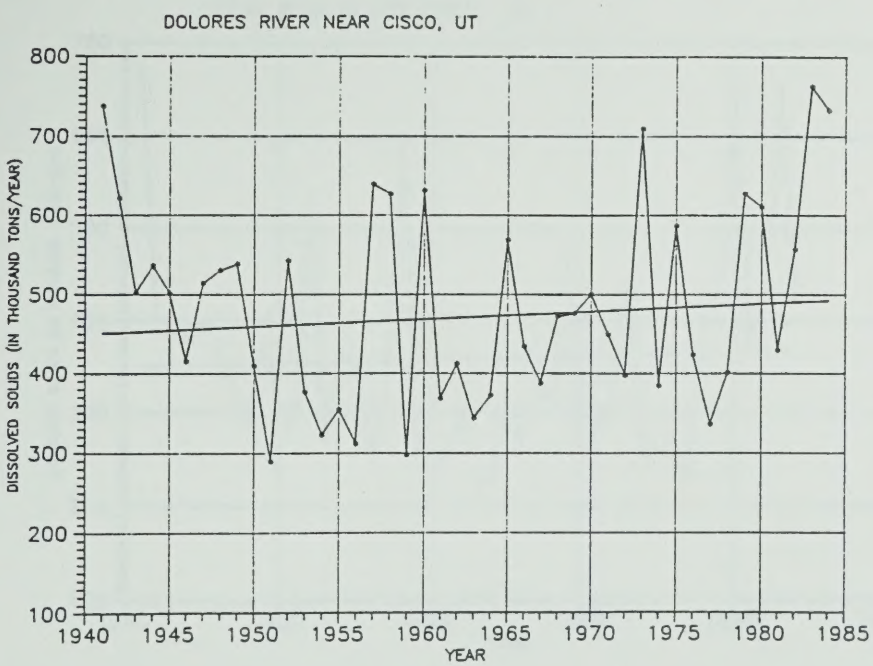

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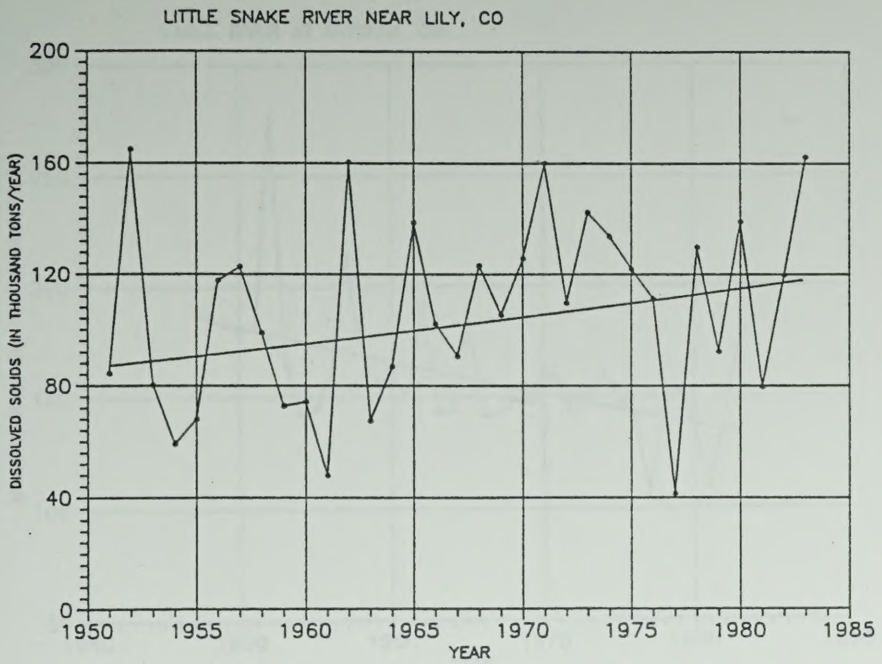

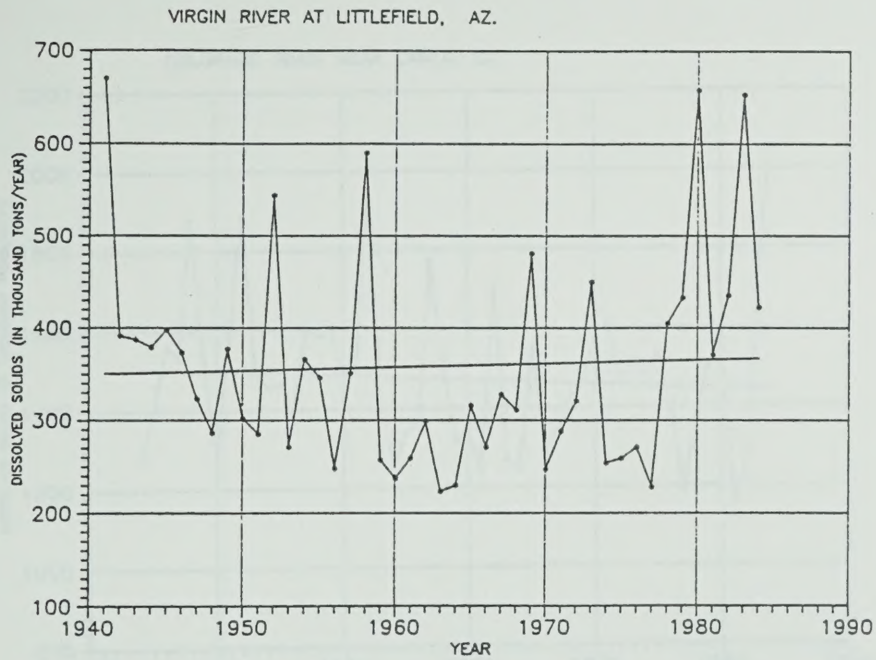

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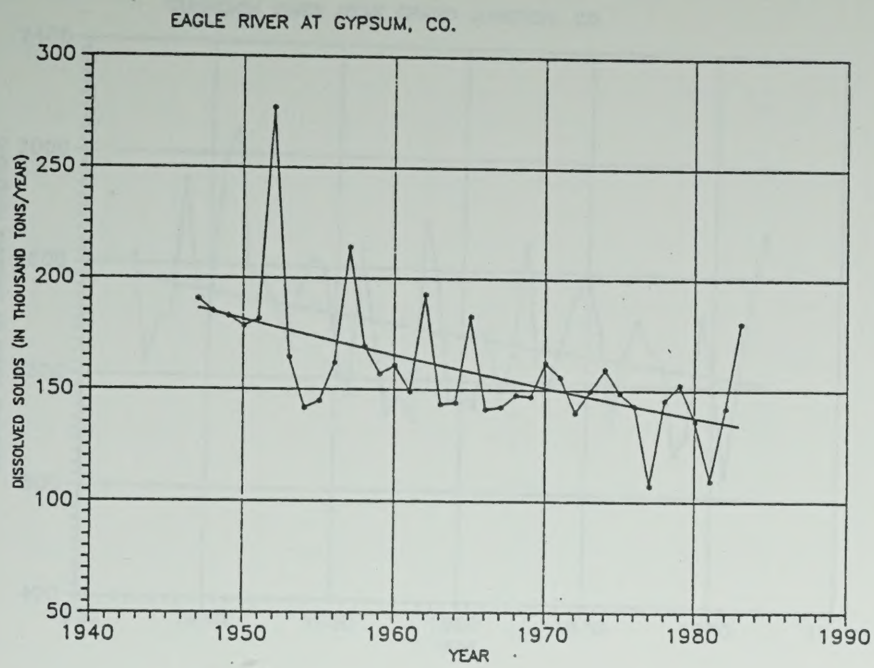

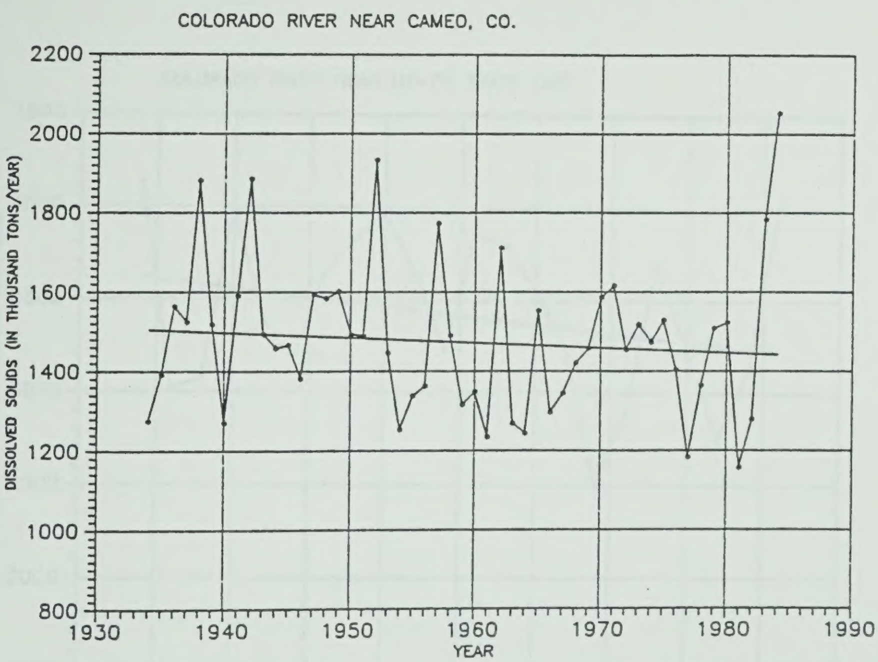

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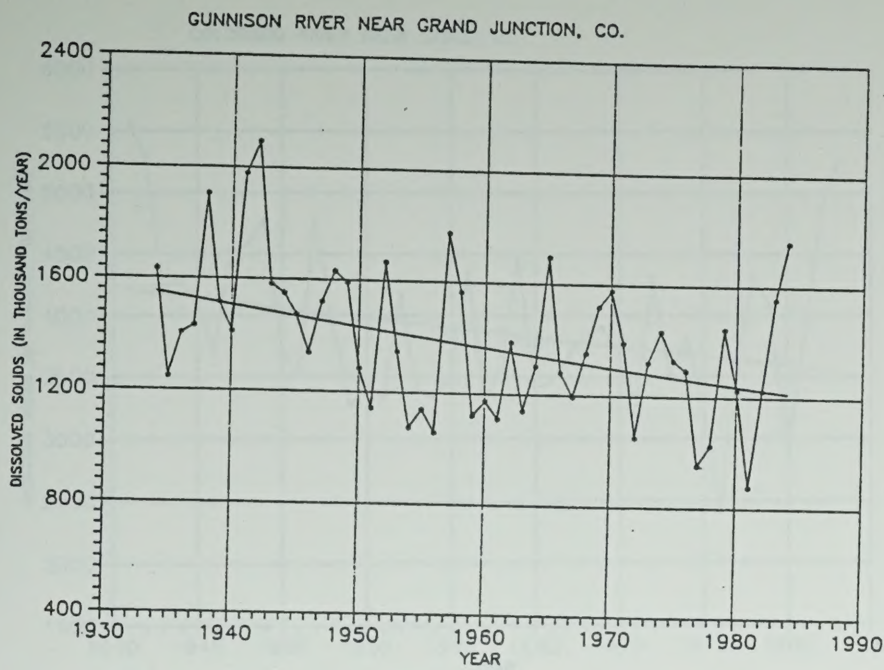

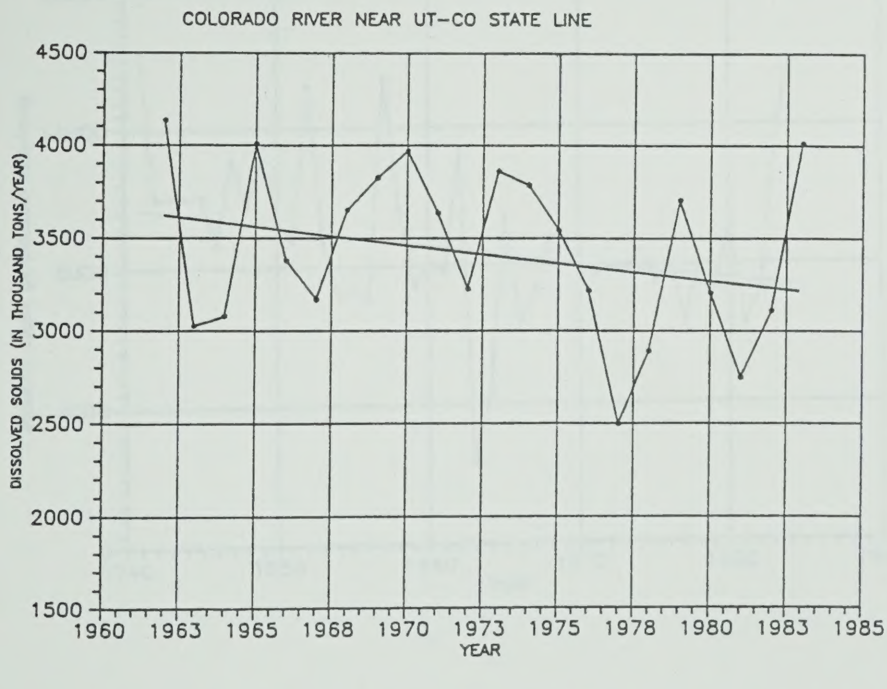

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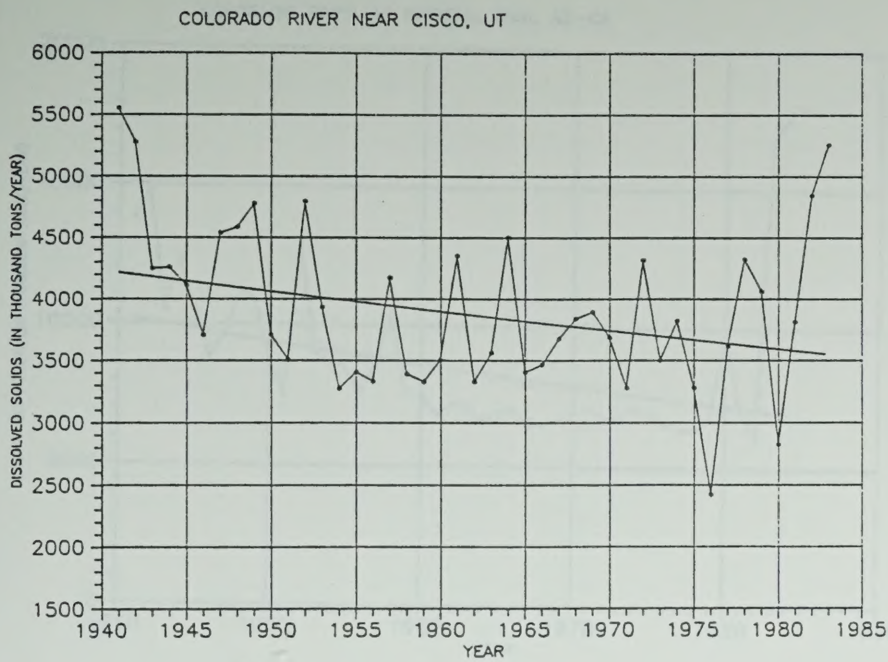

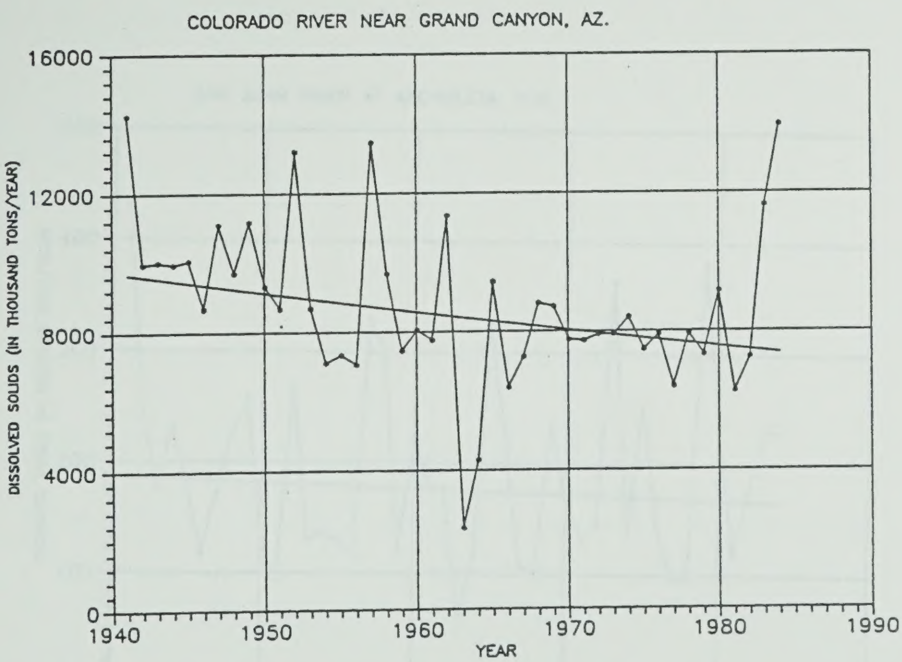

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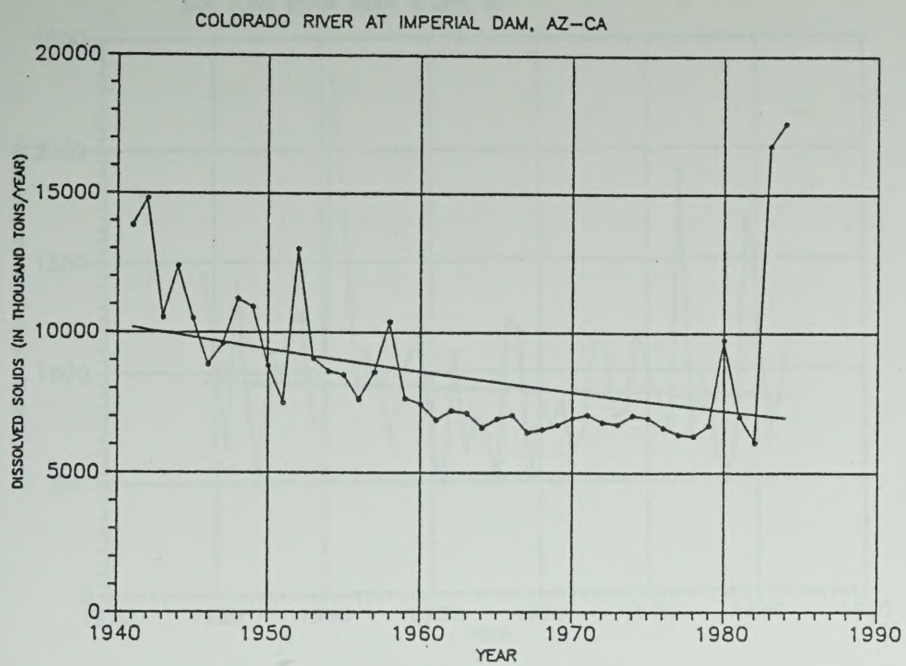

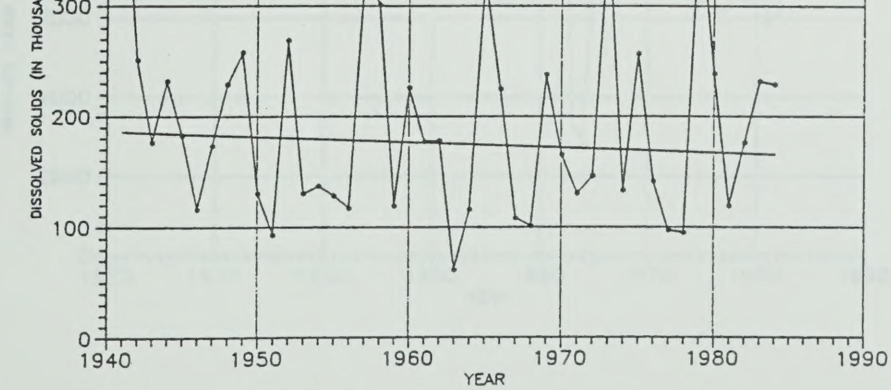

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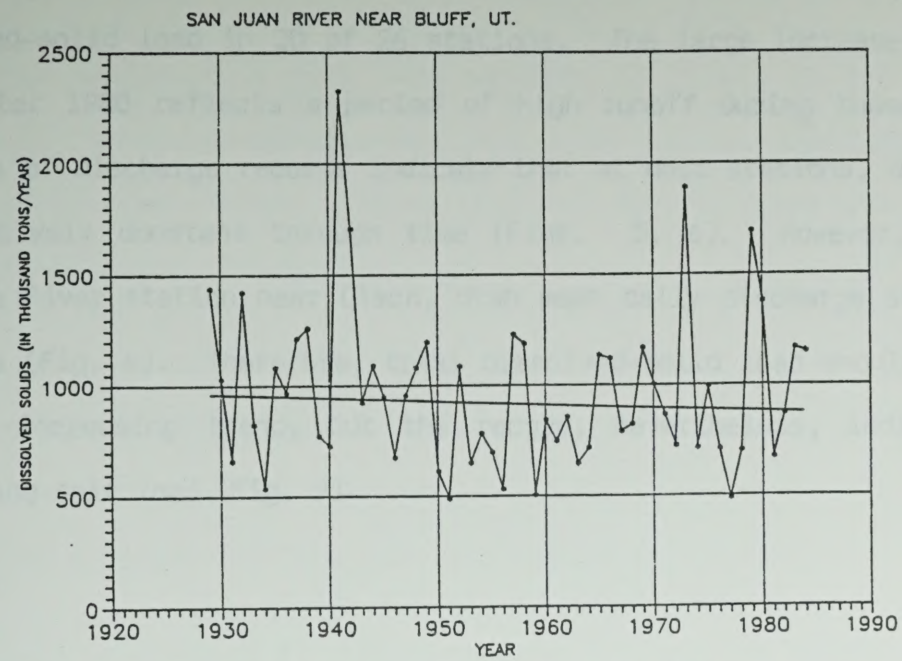

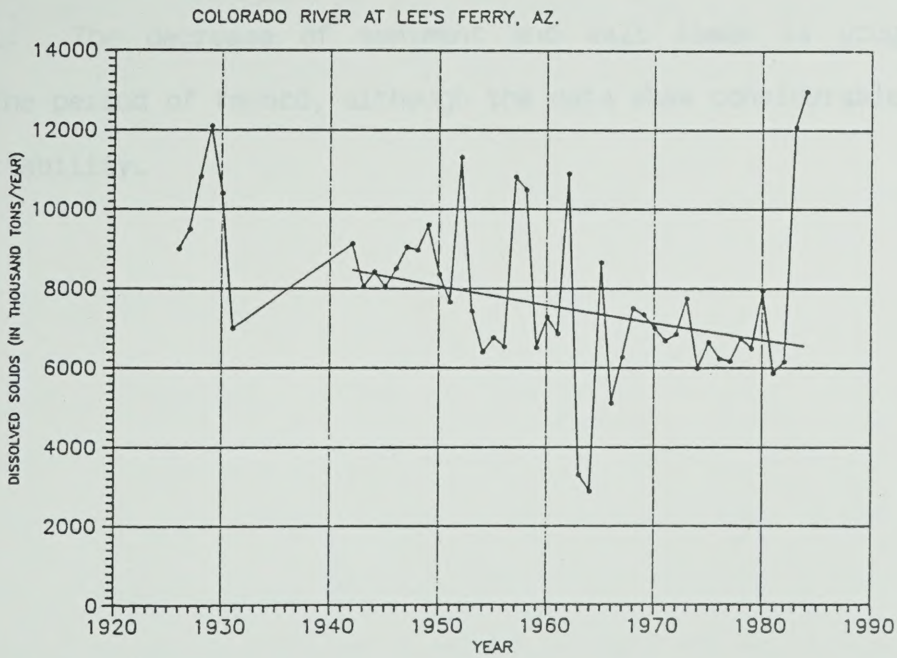

Figure 9 Continued.

findings are in agreement with Kircher (1984) who found a decrease in dissolved-solid load in 20 of 26 stations. The large increase in salt load after 1980 reflects a period of high runoff during those years. Analysis of discharge records indicate that at most stations, discharge is relatively constant through time (Figs. 5, 6). However, at the Colorado River station near Cisco, Utah mean daily discharge showed an increase (Fig. 6). Therefore, total dissolved-solid load should show a related increasing trend, but the record, nevertheless, indicates a decreasing salt load (Fig. 9).

Summary:

The analysis of suspended-sediment and salt loads for the period of record in the upper Colorado River basin shows a decrease of both from 1940 to 1980 at most stations, while discharge remained relatively constant. The decrease of sediment and salt loads is progressive, during the period of record, although the data show considerable year to year variability.

3) HYPOTHESES FOR SEDIMENT AND SALT LOAD CHANGE

Several explanations have been advanced by others to explain the decrease of suspended-sediment and salt loads in the channels of the upper Colorado River basin. The explanations for the suspended-sediment load decrease are as follows:

1) change of sampling procedures
2) effect of climate and hydrologic fluctuations
3) land-management practices
4) arroyo evolution (discussed in Chapter 4).

Explanations related to changes in salt load will be discussed later in this chapter. Explanation 1, that a change in sampling procedures caused a decrease in suspended-sediment loads, needs to be considered first because it casts doubt on the conclusion that a change in sediment load has occurred. Explanation 4, arroyo evolution, is a hypothesis that is tested as part of this Phase I research, and it will be discussed in more detail than the other three explanations in chapter 4.

Sediment Load Reduction

Sampling Procedures: Prior to the early 1940's, field sampling techniques for obtaining suspended-sediment samples were inexact and varied throughout the United States. For example, some of the devices used were: Colorado River Sampler, Ohio River Division Sampler, Faris Sampler used in the Rio Grande River basin, and the Texas Sampler used in the Tulsa District.

As a result of this situation, a team was formed in 1939 to study the methods used in the measurement and analysis of sediment loads in streams. The joint investigation involved several Federal Government agencies: Corps of Engineers, T.V.A., Geological Survey, Bureau of Reclamation, Department of Agriculture, Indian Service, and Iowa Institute of Hydraulic Research. The objective was to test existing sampling methods in an effort to determine reliability and if necessary to develop an improved sampling device. Tests were carried out at the Hydraulics Lab of the Iowa Institute of Hydraulic Research in Iowa City.

The results of one phase of the study indicated that, of the samplers tested, none showed satisfactory results. It was concluded that a sampler should be designed that would provide accurate results. Two improved depth samplers were designed; the US D-43, an integrated depth sampler, and the US P-43, an integrated point sampler (U.S. Interagency Committee of Water Resources, 1940).

Numerous reports published by the U.S. Interagency Committee on Water Resources (1944), compared the results of tests performed with the US D-43 and the Colorado River Sampler. The tests indicate that the new sampler yielded 16% higher values of suspended-sediment concentrations (Table 1). Therefore, the US D-43 sampler should yield higher concentrations of sediment than the Colorado River Sampler, and suspended-sediment measured after introduction of the US D-43, should indicate an increase, not a decrease of suspended-sediment load, as was reported by Thomas et al. (1963), Hadley (1974) and Graf (1985).

It should also be noted that in the San Juan River at Bluff, Utah (Thompson, 1982, p. 10) the significant decrease in suspended-sediment

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Table 1 Comparison of results of tests of the Colorado River Sampler and the US D-43 Sampler.

REPORT*	LOCATION OF TESTS	RATIO = Col. R. Sampler / US D-43
A	San Juan R near Bluff, Ut	0.83
B	San Juan R. near Bluff, Ut	0.64
	Green R. at Green R. Ut	0.95
C	San Juan R. at Shiprock, N.M.	1.03
D	Colorado River at Grand Canyon, Az	1.00
Nelson & Benedict (1950)	San Juan R. near Bluff, Ut	0.82

* Reports A-D from, U.S. Interagency Committee on Water Resources, 1944.

load occurred in 1942 (Fig. 6), but the sampling methods at this station were changed on May 1, 1944. Therefore, the decrease of suspended-sediment cannot be related to the change in sampling methods.

Hydrology: The years 1940-1942, were hydrologically significant in the Colorado Plateau. The period was characterized by high annual discharge, high peak flows (Fig. 10) and high suspended-sediment loads (Table 2). The peaks of suspended-sediment load are coincidental with years of high discharge and peak flows, 1941-1942. The relation of suspended-sediment to discharge is logarithmic, but it contains a wide amount of scatter. Generally speaking an increase in discharge is accompanied by an increase in suspended-sediment. Leopold and Maddock (1953) approximated the relationship as: $L=pQ^j$ where L is sediment load in tons per day, p and j are numerical constants. At-a-station suspended-sediment load usually increases more rapidly than does discharge.

Analysis of longer records of discharge and suspended-sediment loads (Fig. 6), indicates that although discharge affects sediment loads, there must be another factor that is contributing to the decrease of sediment loads with time.

Another way of examining the runoff and sediment-load data is to compute the normalized mean annual suspended-sediment load (tons/day) and to plot this against mean annual discharge and year of record (Fig. 11). The normalized mean annual suspended-sediment load is the mean annual suspended-sediment for a particular year divided by the average suspended-sediment load for the period of record. These plots also

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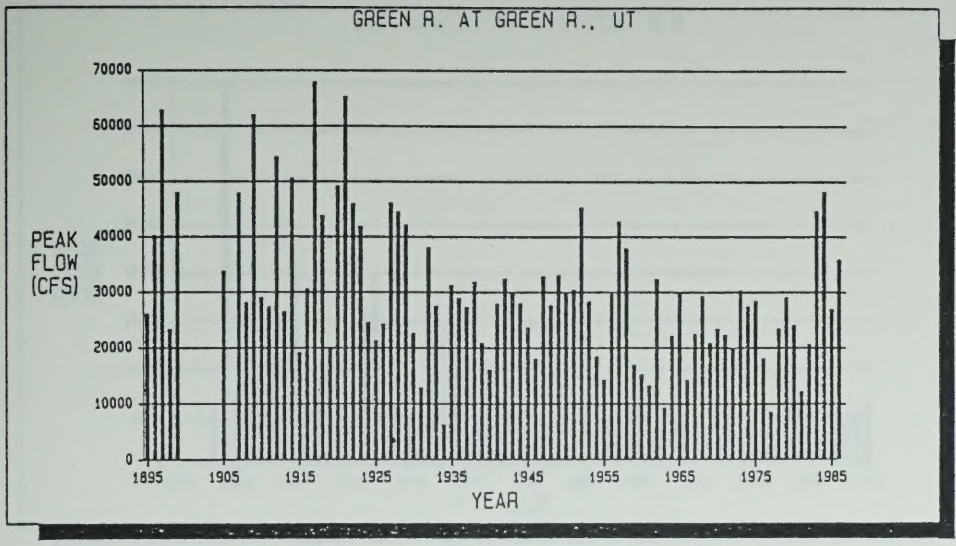
Table 2 Years of significant hydrologic events in the main streams of the Colorado River basin, 1938-1947.

RIVER	PEAK FLOW	HIGH DISCHARGE	HIGH SUS.SED	LOW SUS.SED.	LOW DISCHARGE
San Juan R. near Bluff, Ut	1942	1941,42	1941,42	1939,40 1943	1943
Colorado R. at Grand Canyon, Az	1940	1941,42	1941,42	1939,40	1939-40 1944-46
Green R. at Green R., Ut	---	---	1941,42	1940	1940
Colorado R. near Cisco, Ut	1941,42	1941,42	1941,42	1940	1940 1943
Colorado R. at Lee's Ferry, Az	1941				
Paria R. at Lee's Ferry, Az	1940	1939			
Virgin R. at Littlefield, Az	1938	1938 1941,42			
Navajo R. at Edith, Co	1941,42	1941,42			1939,40 1943



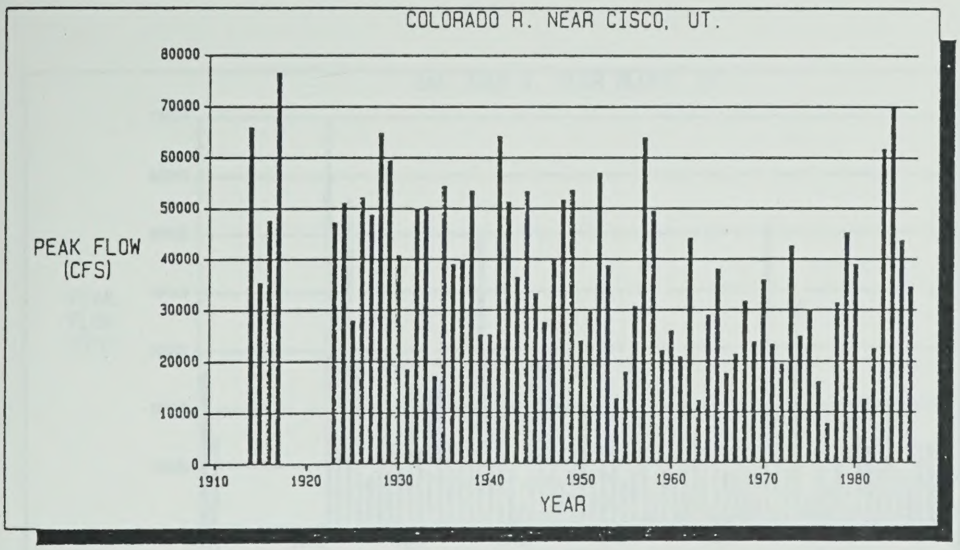
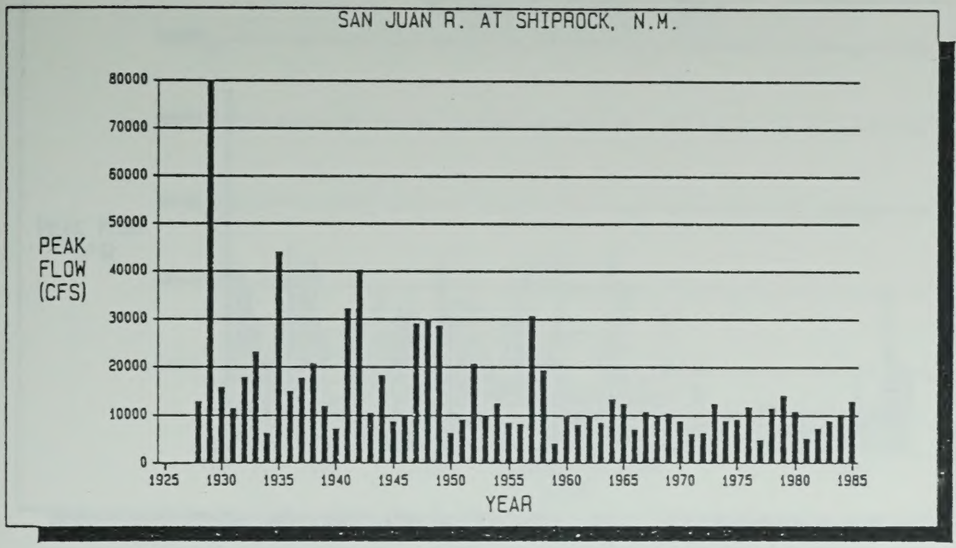
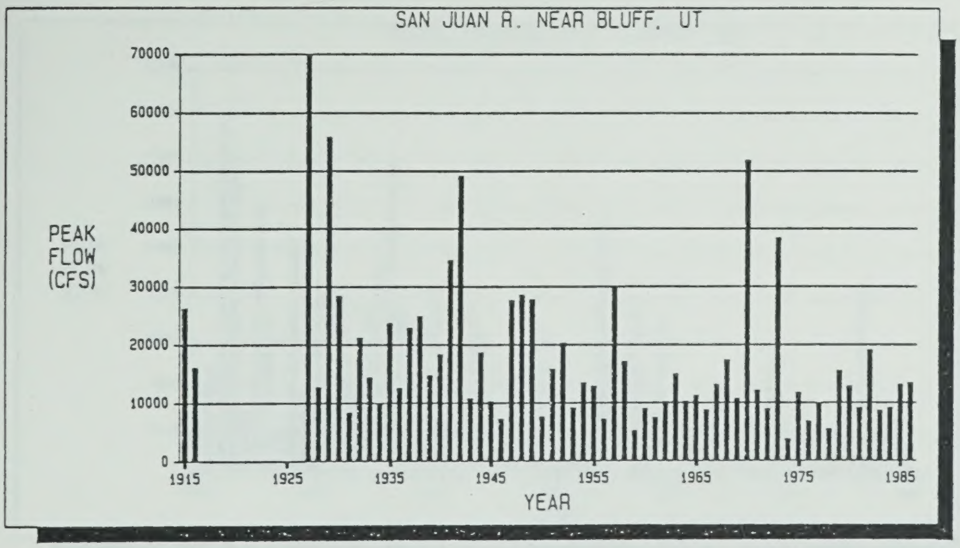


Figure 10 Annual peak discharge for stations in the Colorado Plateau.





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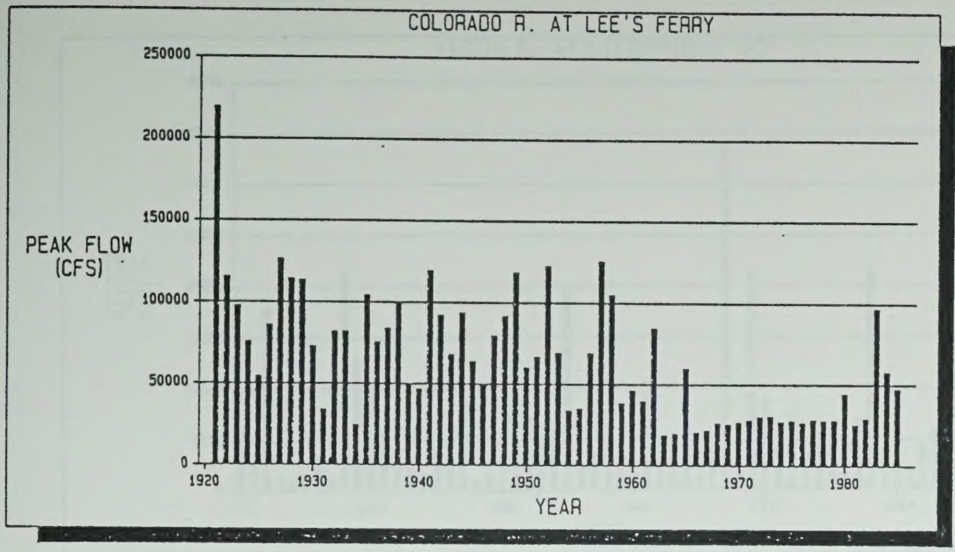

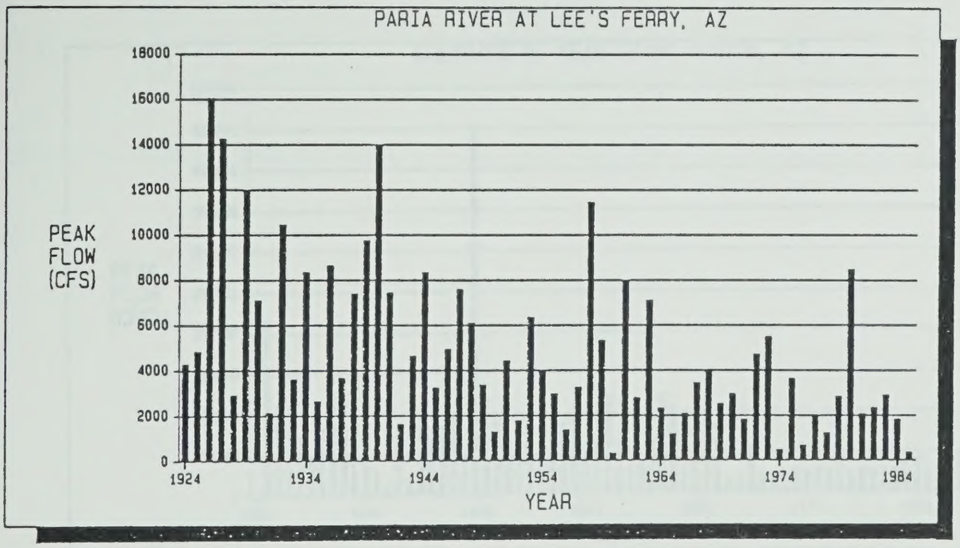

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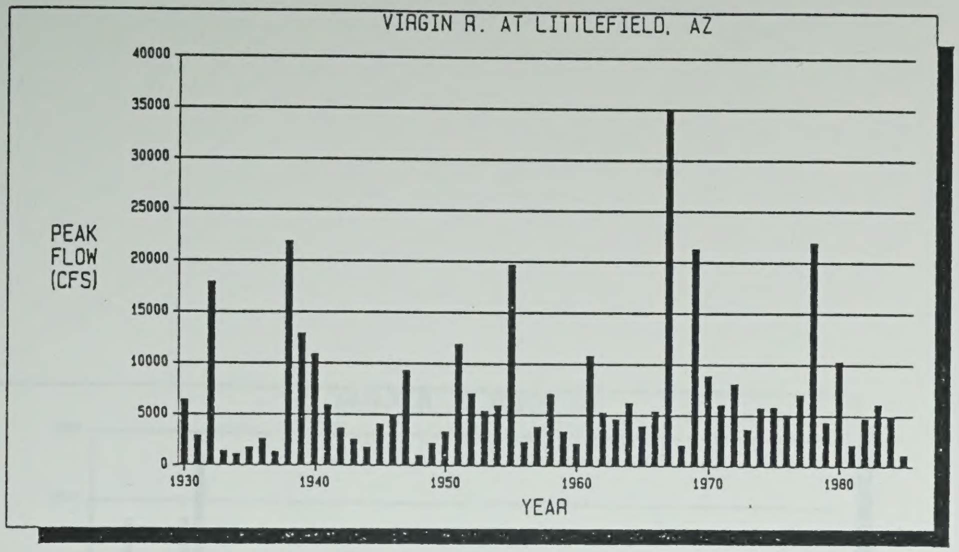

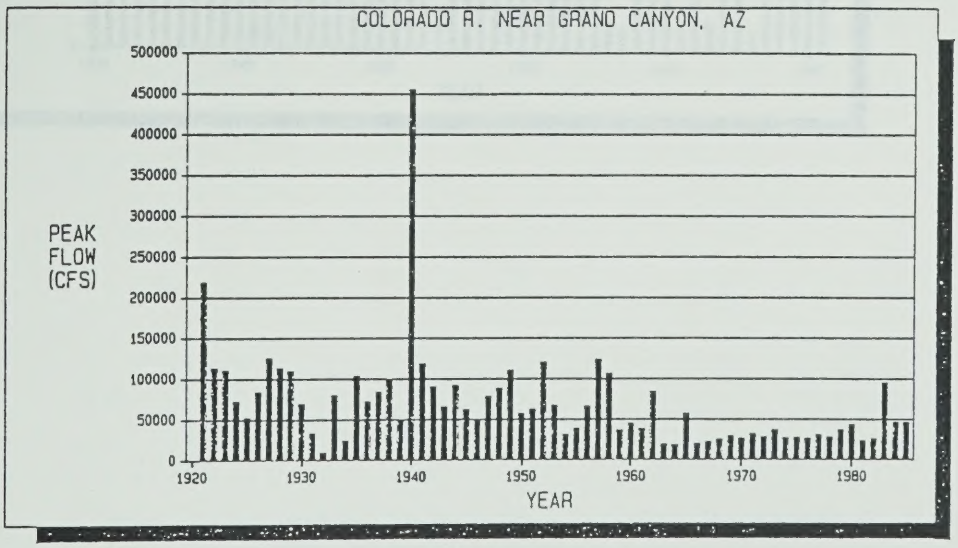

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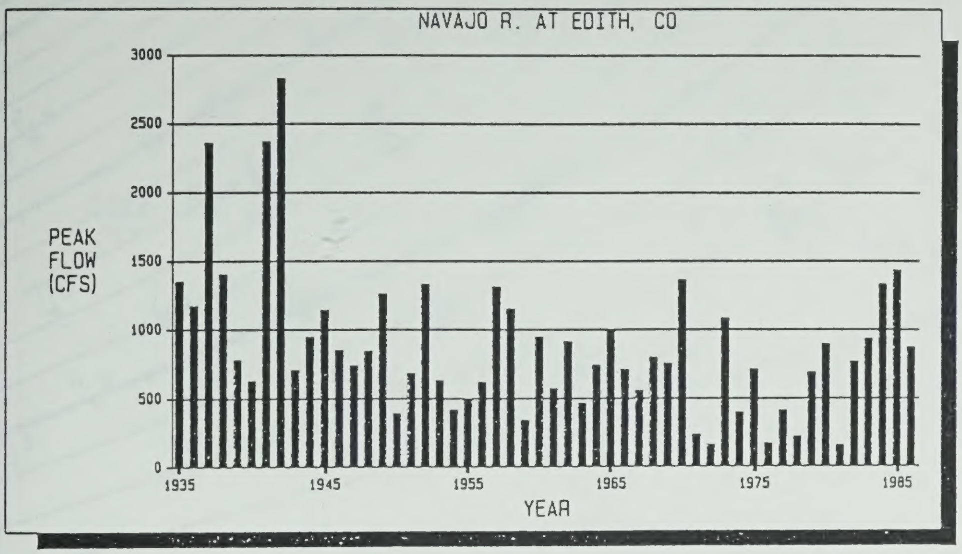

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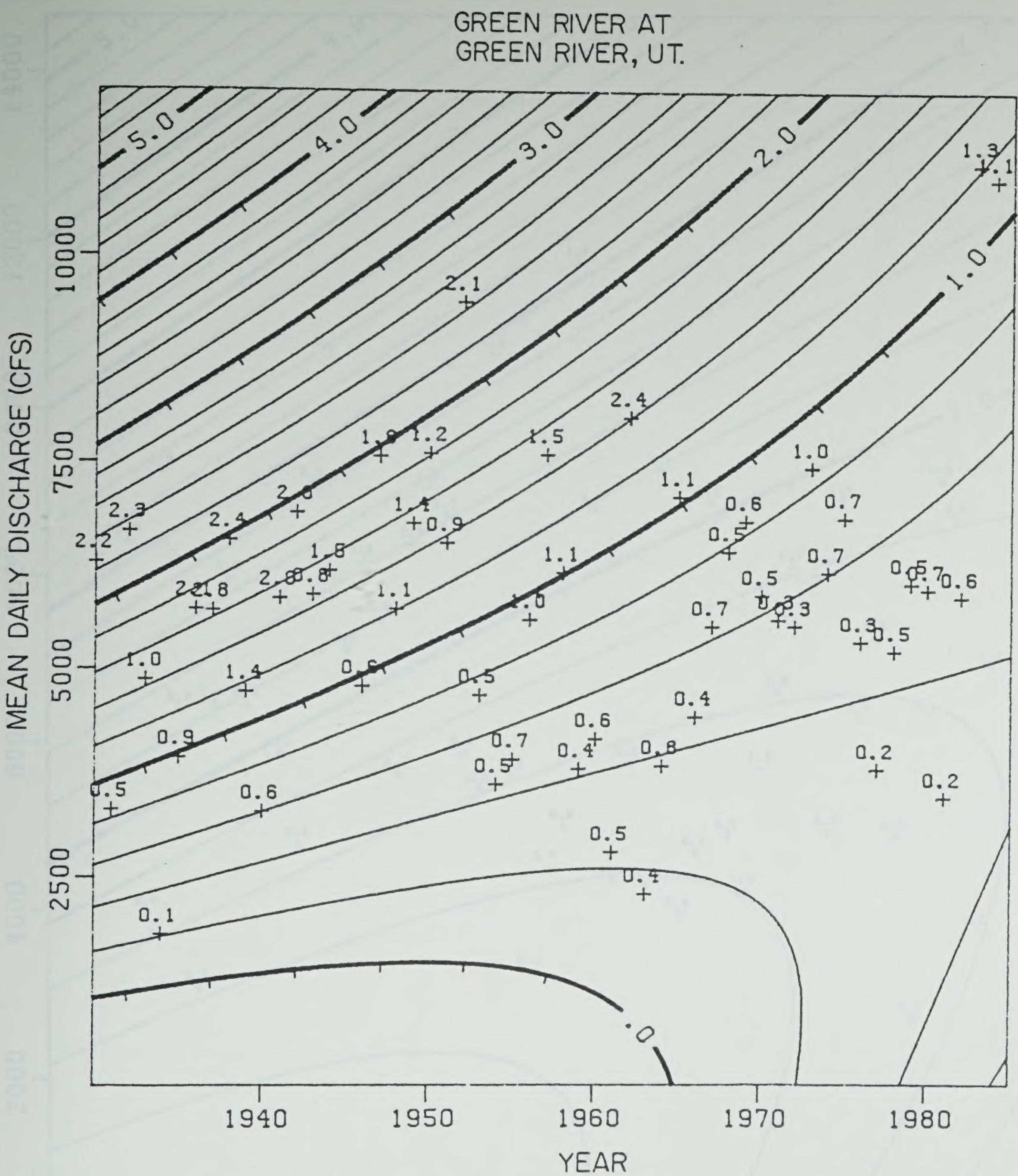
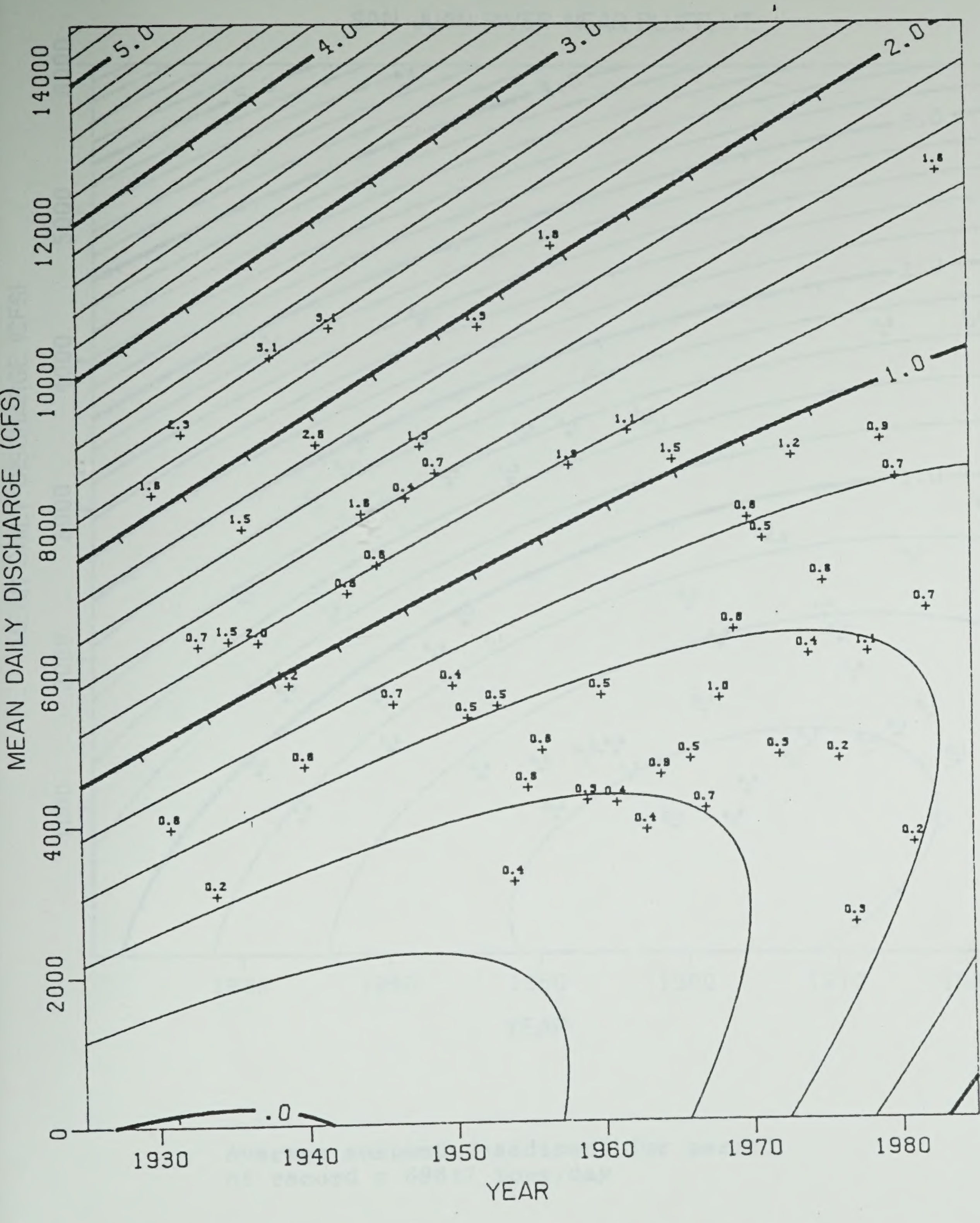


Average suspended-sediment for period of record = 43153 tons/day

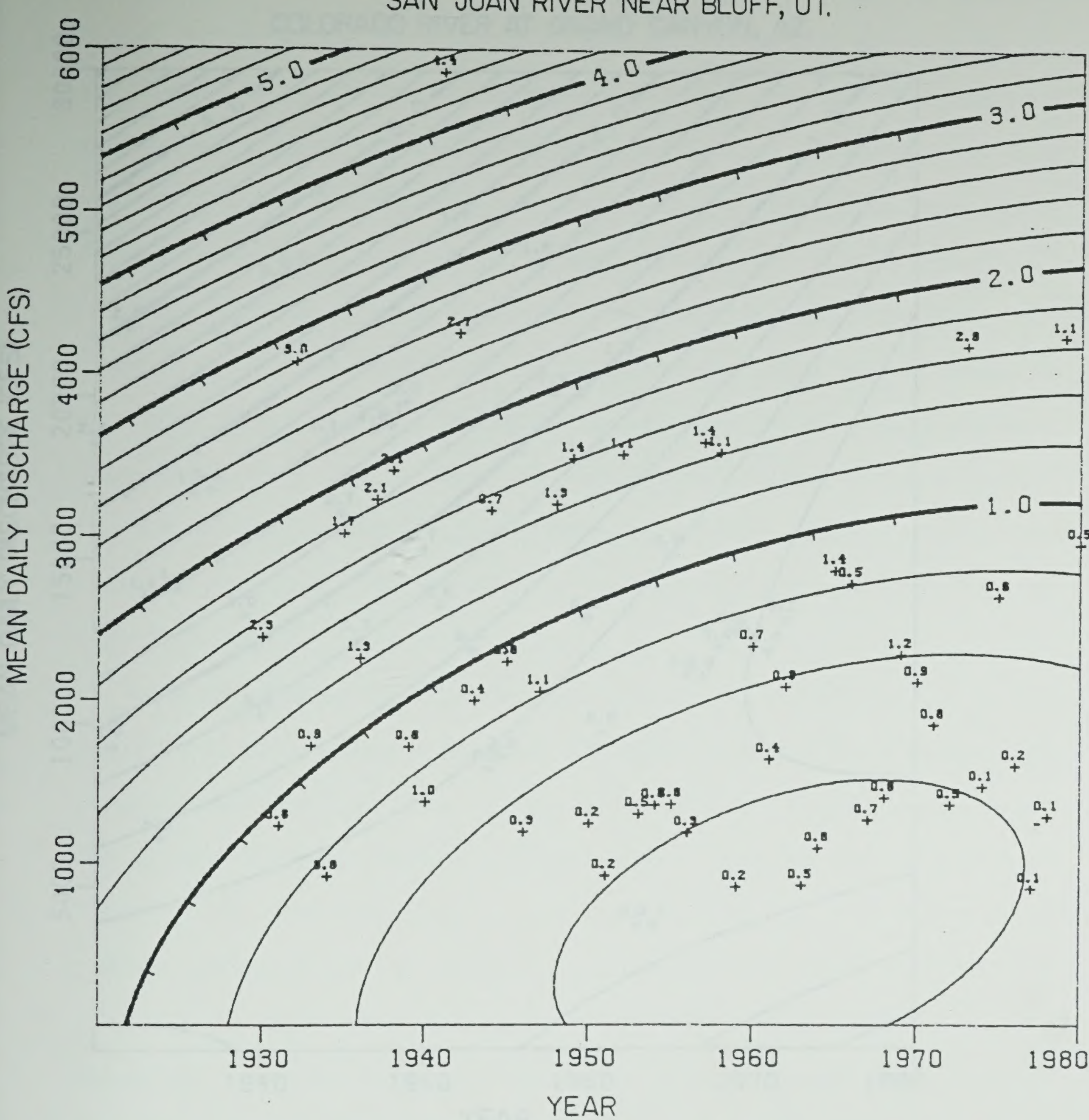
Figure 11 Surface trend map of normalized suspended-sediment load plotted against discharge and year of record. Ratios are representative of mean annual suspended sediment in tons per day divided by the average suspended sediment for the period of record.

COLORADO RIVER NEAR CISCO, UT.



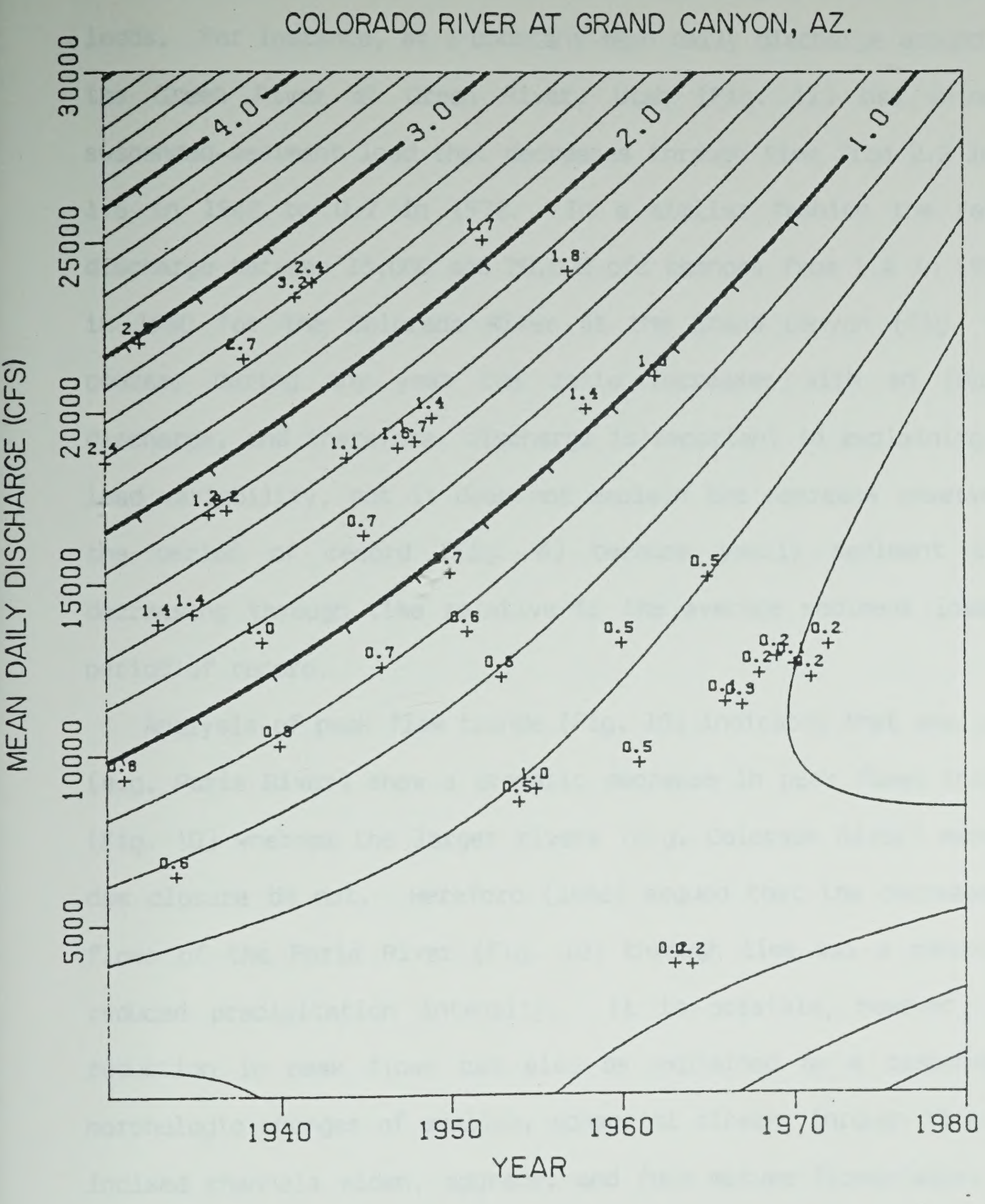
Average suspended-sediment for period of record = 31993 tons/day

Figure 11 Continued.



Average suspended-sediment for period
of record = 69617 tons/day

Figure 11 Continued.



Average suspended-sediment for period
of record = 237284 tons/day

Figure 11 Continued.

indicate that some factor other than discharge is affecting sediment loads. For instance, at a constant mean daily discharge around 6000 cfs the Green River at Green River, Utah (Fig. 11) has a normalized suspended-sediment load that decreases through time from 2.2 in 1930 to 1.6 in 1942 to 0.7 in 1972. In a similar fashion the ratio at a discharge between 15,000 and 20,000 cfs changes from 1.4 in 1938 to 0.5 in 1960 for the Colorado River at the Grand Canyon (Fig. 11). Of course, during any year the ratio increases with an increase of discharge, and therefore, discharge is important in explaining sediment load variability, but it does not explain the decrease observed during the period of record (Fig. 6) because yearly sediment loads are decreasing through time relative to the average sediment load for the period of record.

Analysis of peak flow trends (Fig. 10) indicates that smaller rivers (e.g. Paria River) show a dramatic decrease in peak flows through time (Fig. 10) whereas the larger rivers (e.g. Colorado River) except after dam closure do not. Hereford (1986) argued that the decrease in peak flows of the Paria River (Fig. 10) through time was a consequence of reduced precipitation intensity. It is possible, however, that the reduction in peak flows can also be explained as a response to the morphologic changes of smaller, ephemeral streams through time. As the incised channels widen, aggrade, and form mature floodplains, overbank flooding and backwater effects reduce the peak discharge. Walling et al., (1986) showed that formation of floodplains induces overbank flooding and decreases peak discharges and causes sediment deposition in the vegetated floodplain.

In addition to channel shape, floodplain vegetation increases the hydraulic roughness (n) of the channel, which decreases velocity and flood peak discharge. Wilson (1973) observed changes in stream velocity as a result of increases in foliage, from 7.8 feet per second in a clean channel to 2.0 feet per second in a densely vegetated channel. Harvey and Watson (1987) showed that n values increased from 0.035 to 0.057, in incised channels, as vegetation size and density increased. They also demonstrated that the increased n values were associated with lateral and vertical accretion of sediment. Therefore, although precipitation events certainly affect peak flows, other factors such as channel shape and roughness will also produce changes in peak discharge.

Hereford (1986) indicated that aggradation in Paria River was probably due to periods of low flows that enabled vegetation to take hold thereby promoting vertical accretion and aggradation. There appears to be a positive feedback because as flood peaks decrease more area of the floodplain is available for vegetation colonization. This further increases roughness and accelerates vertical accretion, which further decreases peak flows.

<u>Land - Management Practices</u>: Hadley (1974) and Toy and Hadley (1987) argue that significant decreases in grazing pressures and major soil conservation efforts resulted in, at least, part of the sediment load decrease. For example between 1941 and 1955 the number of sheep and goats in the upper Colorado River Basin was reduced by nearly 750,000, and numerous reservoirs and erosion-control structures were built.

In addition to channel shape, floodplain vegetation increases the hydraulic roughness (n) of the channel, which decreases velocity and flood peak discharge. Nelson (1979) observed changes in stream velocity as a result of increases in foliage, from 7.6 cubic feet per second in a clean channel to 2.0 feet per second in a densely vegetated channel. Hadley and Watson (1967) showed that n values increased from 0.035 to 0.045, in incised channels, as vegetation size and density increased. They also demonstrated that the increased n values were associated with lateral and vertical accretion of sediment. Therefore, although the inflation events certainly affect peak flows, other factors such as channel shape and roughness will also produce changes in peak discharge.

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It is difficult to evaluate the effects of these changes on the San Juan, Green and Colorado Rivers, where sediment and salinity measurements are made, but they would certainly be effective locally (Lusby, 1970). Perhaps some reduction of sediment loads in the large rivers can be expected, but the effects of the land-use changes will be attenuated rapidly in a downstream direction.

Salt Load Reduction

Reasons for the decrease in salt loads through time (Fig. 9) have been postulated as follows:

1) Construction of the Colorado River storage project reservoirs in the 1960's (Moody and Mueller, 1984, p. 47).

2) Improved grazing practices.

3) Improved irrigation techniques.

4) Point source control - The U.S. Department of Interior (1987, p. IX-3) identified two stations that reflected point salinity control (White River near Watson, a control of 57,000 tons annually and Reed Wash near Loma, a control of 18,000 tons annually).

5) Hydrologic Variables - Because increased runoff increases total yields of dissolved solids, a decreasing trend in discharge through time could affect total dissolved-solid loads.

Several studies have related salinity to hydrologic variables. Langbein and Dawdy (1964) found that with an increase in runoff the dissolved-solid load increases until a point is reached where the rate of dissolution becomes the controlling factor (Fig. 12). Nezafati, et al. (1981) found that, as the suspended load and bedload increase, the dissolved load will increase, and Jackson et al. (1984) demonstrated that salt release is 3.8% of sediment yield. Therefore, as runoff and erosion increase, salt production will increase.

Moody and Mueller (1984) suggested that decreasing trends in salinity, are the result of the B.L.M's land-use practices and reservoir building in the 1960's. However, only about 50% of the salt load in the Colorado River is derived from natural sources (Jonez, 1984), and therefore, any connection between a decrease of sediment load and salt load will be masked by the 50% contribution from irrigation and other human activities. Nevertheless, salt loads can be reduced by decreased erosion of saline shales (Fig. 7), and therefore, land use and conservation measures will be effective in reducing salt loads.

Summary

Of the four explanations for the decrease of sediment and salt loads only one, the change of sampling procedures, can be eliminated. Although annual discharge and peak discharge variations, influence annual sediment and salt loads, they do not explain the progressive decrease during the period of record. Improved land-use and conservation measures probably have decreased both sediment and salt loads, but the magnitude of these effects cannot be determined.

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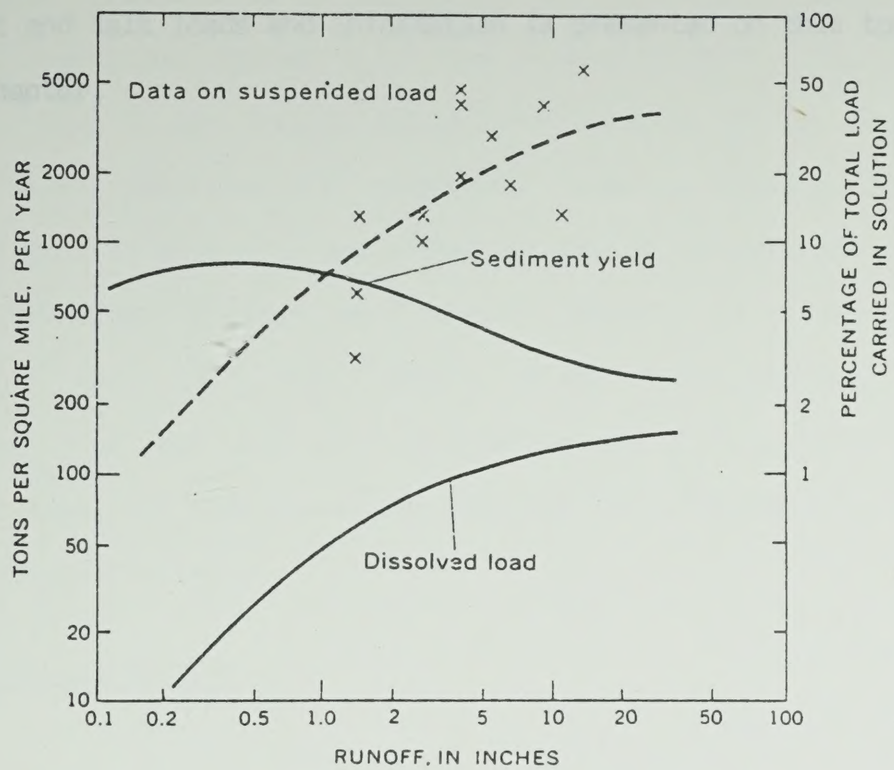

Figure 12 Comparison between dissolved-solids load, suspended-sediment load, and sediment yield of rivers (after Langbein and Dawdy, 1964).

As Figure 11 suggests, other factors are acting to decrease sediment and salt loads, and these certainly involve the geomorphic changes that are part of the evolution of arroyo morphology (Fig. 14), since their development in the late 19th century. A major objective of this Phase I project was to investigate the effects of channel evolutionary processes on sediment and salt loads and information is presented on this topic in the next chapter.

4) ARROYO EVOLUTION

The recent period of arroyo cutting, 1865-1915, in the Southwest involved the formation of hundreds of arroyos in several states, in many drainages, and under a wide variety of environments (Fig. 1). Valleys that formerly supported dense vegetation and high water tables, were incised in some cases to depths of over a hundred feet. The results were devastating to the fragile agricultural economy of the area, and many small towns and farms were abandoned. However, research into the Holocene history of arroyos reveals that periods of incision and filling were not restricted to this past century (Bryan, 1941; Hack, 1942; Cooley, 1962; Hall, 1977; Graf, 1987). Study of the alluvial valley fills reveal that cut and fill episodes occurred frequently during prehistoric time. Of more importance here are the 19th-century changes, which are reviewed briefly.

History of Arroyo Cutting

Swift (1926) recounts a conversation with a local rancher about the country around the Gila Valley, southern Arizona. The rancher described the area as consisting of fields of grass in 1884, "The Gila was a very small stream confined in a narrow shallow channel the banks of which were lined with willows, brush and sod grasses". After a drought ended in 1899, floods followed for five years, which quickly melted away the river banks.

Bryan (1925) published a description of the Chaco Canyon arroyo in northern New Mexico as described by Lt. Simpson in 1849. Simpson stated

that the Rio Chaco was eight feet wide and one and a half feet deep. The Chaco arroyo, at the time of Bryan's work in 1925, was 150-450 feet wide and 20-30 feet deep. Bryan dated the incision at around 1870. In Walker Creek and Chinle Creek, located in the northern portion of the Navajo Reservation, Indians were cultivating the alluvial floor as late as 1894. In 1913 Walker Creek flowed in an arroyo 80 feet wide and Chinle Creek was 100 feet deep. The incision occurred in about 1880 (Gregory, 1917). Bryan's summary of dates of incision in the Southwest, was for southern Arizona, 1880-1890; southern Utah, northern Arizona and southern Colorado, some time after 1860; the Rio Puerco of New Mexico, 1846-1847.

Colton (1937) gives accounts of the Little Colorado River between Holbrook and Cameron in Arizona. From a description of the Spanish explorer Espejo, who visited the valley in 1583, (Luxan, 1929), "(We) reached a fine, beautiful, and selected (SIC) river almost as large as the Del Norte, containing many groves of poplars and willows." Farfen and Quesada, two other explorers, crossed the Little Colorado in 1598 and named it the "Rio Alameda", the river of groves. The Little Colorado, in 1937 was flowing in a wide treeless valley, with steep cut banks and a sandy bed (Colton, 1937). "On either side of the river rise low sandy and gravelly hills almost free of vegetation." Colton further mentions a house built by a settler in 1878, 100 feet from the banks of the Little Colorado. In 1935 the river was cutting into the foundations of the structure. In 1937, two years later, the river widened a further 14 feet, and destroyed the structure.

That arroyos can incise at incredibly rapid rates, is documented by accounts of Kanab Creek, Utah (Gregory, 1917). In three years,

that the Rio Chaco was eight feet wide and one and a half feet deep. The Chaco arroyo, at the time of Bryan's work in 1925, was 150-450 feet wide and 20-30 feet deep. Bryan dated the incision at around 1870. In Walker Creek and Chinle Creek, located in the northern portion of the Navajo Reservation, Indians were cultivating the alluvial floor as late as 1890. In 1913 Walker Creek flowed in an arroyo 80 feet wide and Chinle Creek was 100 feet deep. The incision occurred in about 1880 (Gregory, 1917). Bryan's summary of dates of incision in the Southwest, was for southern Arizona, 1880-1890; southern Utah, northern Arizona and southern Colorado, some time after 1880; the Rio Puerco of New Mexico, 1885-1887.

Colton (1937) gives accounts of the Little Colorado River between Holbrook and Cameron in Arizona. From a description of the Spanish explorer Espejo, who visited the valley in 1583, (Colton, 1937): "[We] reached a fine, beautiful, and selected river almost as large as the Del Norte, containing many groves of poplars and willows." Garces and Guevara, two other explorers, crossed the Little Colorado in 1776 and named it the "Rio Alameda", the river of groves. The Little Colorado, in 1937 was flowing in a wide treeless valley, with steep cut banks and a sandy bed (Colton, 1937). "On either side of the river rise low sandy and gravelly hills almost free of vegetation." Colton further mentions a house built by a settler in 1876, 100 feet from the banks of the Little Colorado. In 1935 the river was cutting into the foundations of the structure. In 1937, two years later, the river widened a further 15 feet, and destroyed the structure.

That arroyos can incise at incredibly rapid rates, is documented by accounts of Kanab Creek, Utah (Gregory, 1917). In three years,

1885-1888 a gully 60 feet deep, 70 feet wide, 15 miles long, formed in the Kanab valley.

While conducting field work for this study, at the Tusayan Washes in Northern Arizona (Fig. 13), a local Indian recalled his grandmother saying that the water in the Oraibi Valley was so high, you could see water shimmering on the surface of the valley, as the sun set. Today the Oraibi Wash at Oraibi Town is an arroyo 80 feet wide and 25 feet deep.

These accounts of early settlers and explorers afford a view of the changes that took place in drainage characteristics and vegetation in the valleys of the Southwest during the last few centuries. The commencement of arroyo cutting, although not occurring simultaneously everywhere, is the starting point for a discussion of sediment and salt load changes during the last 100 years.

Causes of Arroyo Cutting

Understanding the processes that cause such a widespread phenomenon as arroyo cutting is essential to the development of strategies for erosion and water quality control. The causes and timing of arroyo cutting have encouraged much debate, with a voluminous amount of literature. Cooke and Reeves (1976) provide an excellent review of the subject. Causes of arroyo incision have been generally assigned to either human activities or natural phenomenon. Conclusive proof may never be resolved for either argument, but an explanation for the channel incision is not the objective of this study. Nevertheless, a

brief review of the general hypotheses concerning arroyo cutting may be of value in developing a model of arroyo evolution.

Land Use: A large number of researchers support the concept that human activity in the southwest initiated arroyo cutting. The principle explanation is that large numbers of livestock were introduced in the post Civil War period, which caused overgrazing and serious vegetation removal (Dodge, 1902; Rich, 1911; Duce, 1918; Swift, 1926; Cottam and Stewart, 1940; Thornthwaite et al., 1942, Antevs, 1952). Evidence that arroyo cutting did not take place in valleys before the introduction of livestock, was enough to convince many people that overgrazing was the main cause of incision. However, arroyo cutting did not always occur with livestock introduction, and it did occur during prehistoric times as described above.

Livestock has two effects on the land surface; cattle form trails as they migrate between watering and feeding places, and secondly they remove vegetation by grazing and trampling. Trails channelize water, which promotes gullying and incision (Thornthwaite, et al., p. 70, 1942). Removal of vegetation permits increased gullying and sheet erosion in the sloping uplands and gullying in the valley bottoms (Peterson and Hadley, 1960). Gullying channelizes flow and eliminates overbank flooding, thereby depriving the natural vegetation of moisture. The result is further loss of vegetation, which leaves large areas barren. Raindrop impact on the surface destroys the loose structure of the soil and compacts it to a hard surface. Consequently, surface runoff and stream discharge increase.

Once vegetation is removed, periodic intense storms have devastating effects on the barren landscape. Therefore, it was the belief of many proponents of the overgrazing hypothesis that large storms in 1890-1900, produced the arroyos (Swift, 1926; Cottam and Stewart, 1940; Antevs, 1951). Before livestock intervention, storms of such magnitude would have been less likely to affect the valley floors.

<u>Climate</u>: Past episodes of cut and fill in the geologic record are cited as evidence for a climatic control of recent arroyo cutting. Proponents of this argument believe that a climate change in the 1800's, triggered the incisional episode.

Several categories of climate change have been proposed:

1) increase in precipitation (Huntington, 1914, p. 31-33; Bull, 1964; Hereford, 1984, p. 667).

2) decrease in precipitation (Bryan, 1941), and

3) increase in rainfall frequency (Leopold, 1951; Bull, 1964); Gregory (1917) viewed this as it related to flood events.

Bull (1964) showed that channel trenching in western Fresno County, California was caused by large annual rainfall and also periods of high frequency in large daily rainfalls, and Hereford (1984) examined tree ring width indices and suggested that the erosive phase was initiated in the early 1900's by an increase in moisture.

Bryan (1941) felt that because accelerated erosion had occurred in valleys before the introduction of livestock, other causes than

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Bryan (1941) felt that because accelerated erosion had occurred in valleys before the introduction of livestock, other causes than

overgrazing should be sought. Bryan postulated a climatic cause for epicycles of erosion that assumed runoff is largely regulated by vegetation. During periods of low rainfall there is a sparser vegetation cover, although the individual precipitation events may be of equal or greater magnitude. Consequently runoff is high, violent, and it promotes incision.

Leopold (1951) argued against Thornthwaite's et al. (1942) conclusion, that at the turn of the century (1850-1930), there was not a change in precipitation. Leopold agreed that mean annual precipitation, showed no change, but he demonstrated that there was an increase in the frequency of small precipitation events (0.01-0.49 inches in a day), from 1850-1940 (Table 3). Small events provide the moisture necessary for vegetation growth, whereas large events cause both sheet erosion and gullying. The minor number of small events in the period 1849-1895 may have weakened vegetation, and the large storms that occurred between 1885 and 1890 may have accelerated erosion.

The climate argument is confusing because of the general lack of agreement among writers. By definition (Woolf, 1975), climate is the average course or condition of the weather at a place over a period of years as exhibited by temperature, wind velocity, and precipitation. Movement of air masses controls the weather patterns and precipitation events in the Southwest (Thornthwaite et al., 1942, p. 4). The Southwest is composed of three different rainfall regimes (Thornthwaite et al., 1942). If climate did change, each regime may have responded in a different way. In one rainfall regime, changes in storm intensity may

overgrazing should be sought. Bryan postulated a climatic cause for subcycles of erosion that assumed runoff is largely regulated by vegetation. During periods of low rainfall there is a scanty vegetation cover, although the individual precipitation events may be of equal or greater magnitude. Consequently runoff is high, violent, and it promotes incision.

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Table 3 Average frequency per year of rainfall events of various sizes in four segments of the record, 1850-1948 (from Leopold, 1951, p. 354).

STATION	PERIOD	Size Classes of daily rains, inches			Mean annual rain for period in.
		0.01-0.49	0.50-0.99	>1.00	
Santa Fe	1850-1880	59.7	5.7	1.96	14.5
	1881-1910	80.8	5.5	1.07	14.4
	1911-1930	82.8	5.3	1.20	14.3
	1931-1948	71.5	5.1	1.05	12.9
Las Cruces	1850-1880	23.8	3.8	1.65	7.9
	1881-1910	31.7	4.7	1.17	8.8
	1911-1930	41.1	3.9	0.50	8.4
	1931-1948	42.0	3.3	0.67	8.6
Albuquerque	1859-1880	21.2	1.3	0.40	8.0
	1881-1910	30.5	2.9	0.71	7.7
	1911-1930	47.0	2.6	0.56	8.5
	1931-1948	58.3	3.4	0.67	9.0

have been important, whereas in another rainfall regime increased annual precipitation may have been important. Therefore, hydrologic effects should be examined for a given regime, not over the whole region.

Summary: Arroyos have formed during the last 10,000 years in the Southwest probably as a result of climate change. However, arroyo formation during historic time can be explained by climatic fluctuations, overgrazing, other human activities, and geomorphic controls. No single explanation is satisfactory, and it is probable that the interaction of several factors caused individual arroyo formation. Nevertheless, the coincidence of channel incision with the appearance of European settlers is compelling circumstantial evidence that a large part of the explanation relates to human activities.

Arroyo Evolution

Once arroyo incision begins geomorphological changes result in a new condition of relative stability. Studies of many incised channels reveal that they proceed from the initial incision through a series of evolutionary changes, until they achieve a new condition of relative stability. Channelized-stream evolution in northern Mississippi (Fig. 14) provides a model of this process as follows: 1) deepening, 2) widening, 3) initial deposition and increased bank stability, 4) renewed stability at a lower level.

Thornthwaite et al, (1942) described four stages of arroyo growth for Polacca Wash, Northern Arizona, as follows: 1) initiation, promoted by runoff, 2) enlargement by headward elongation, 3) healing, by a

reduction of slope of the arroyo walls and establishment of vegetation, 4) stabilization, revegetation and development of soil profile, possibly leading to complete filling of the arroyo.

Changes in channel evolution can be described and quantified by using what geomorphologists refer to as the location-for-time substitution (Paine, 1985). When erosion begins at a certain location in a valley and proceeds upstream, the lower valley locations will be more advanced in the channel evolution process than will be the recently incised upstream reaches. Therefore, a comparison of the different channel reaches provides a record of channel change (Fig. 14), and the record can be used to predict what will happen at a single cross section through time.

In order to document such changes in the upper Colorado River basin, channel cross sections were surveyed along Dinnebito Wash and Oraibi Wash, northern Arizona (Fig. 13). Upstream reaches (Figs. 15A, B; 16A, B) are characterized by steep outer walls with straight confined channels, that are actively widening. Large quantities of sediment derived from upstream tributaries and from the collapse of the outer walls, increase sediment supply to the main channel, causing the channel to braid and shift laterally, further widening the channel. Vegetation on the incipient floodplains is scarce and it is periodically removed by high flows.

Middle reaches (Figs. 15B, C; 16B, C) have high steep outer walls that confine a sinuous channel, which is actively building up point bars and floodplains. Vegetation is well developed, with thick stands of salt cedar on the point bars and floodplains.

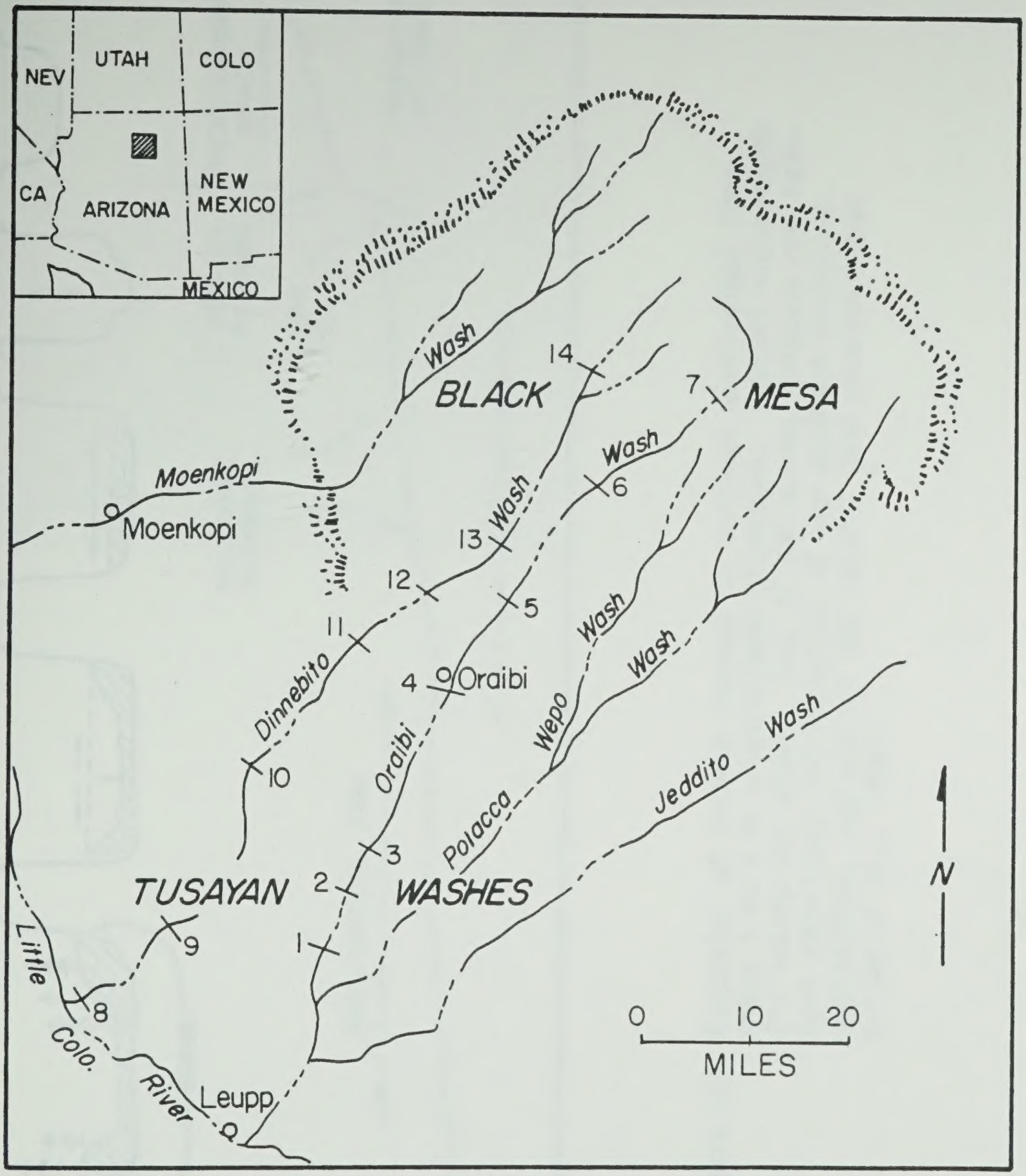


Figure 13 Location map for cross sections and photographs, Oraibi Wash and Dinnebito Wash.

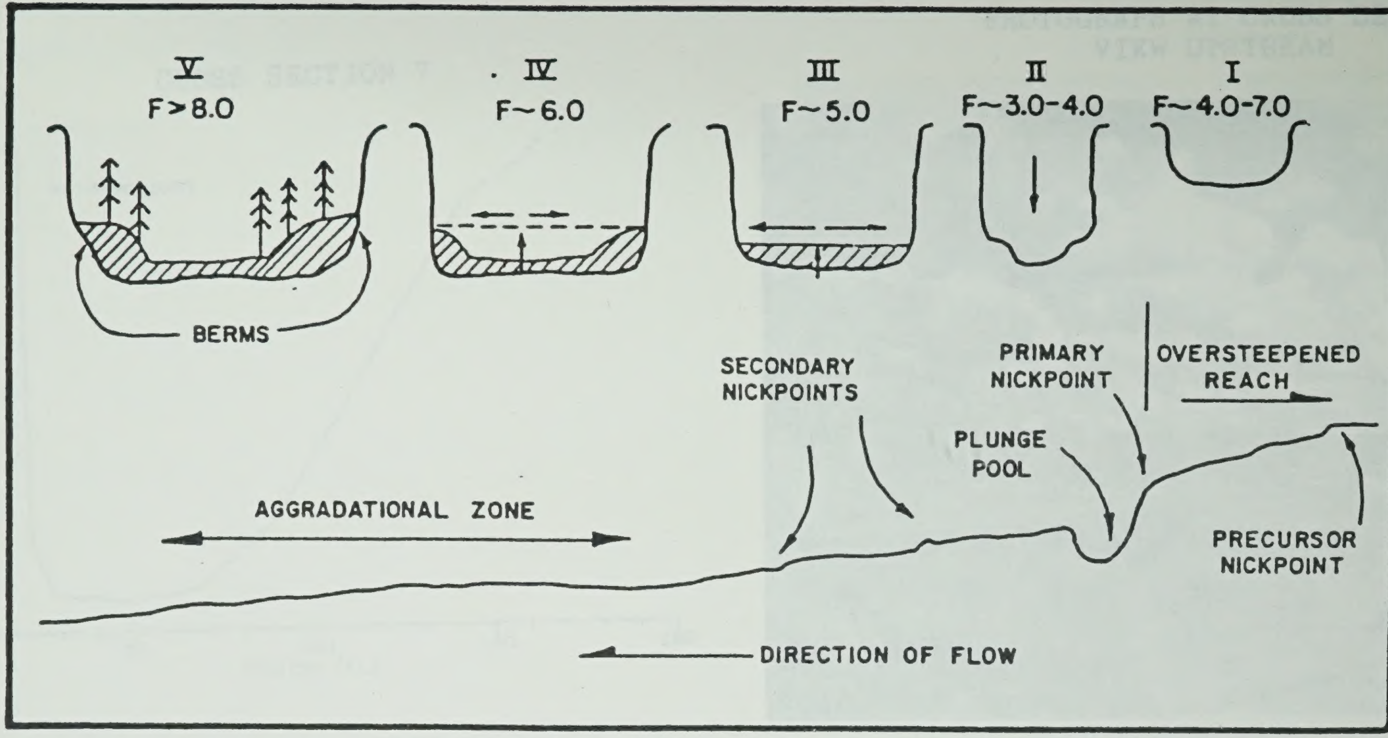
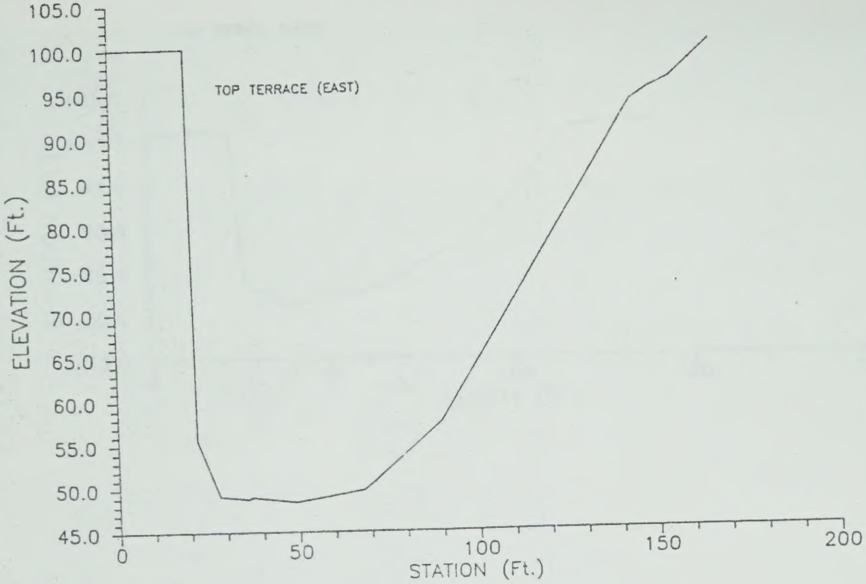
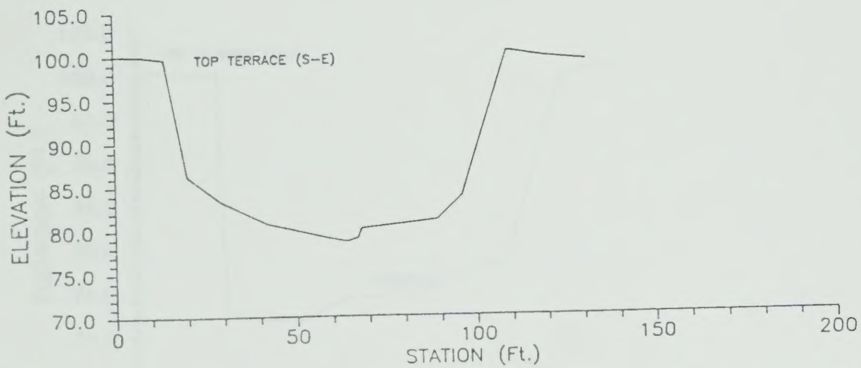


Figure 14 Evolution of incised channel in northern Mississippi from stage I to V in a downstream direction. Typical width-depth (F) values are shown. Size of the arrows indicate the relative importance and direction of the dominant processes, degradation, aggradation and lateral bank erosion (from Schumm et al., 1984).

CROSS SECTION 7



CROSS SECTION 6



PHOTOGRAPH AT CROSS SECTION 6
VIEW UPSTREAM

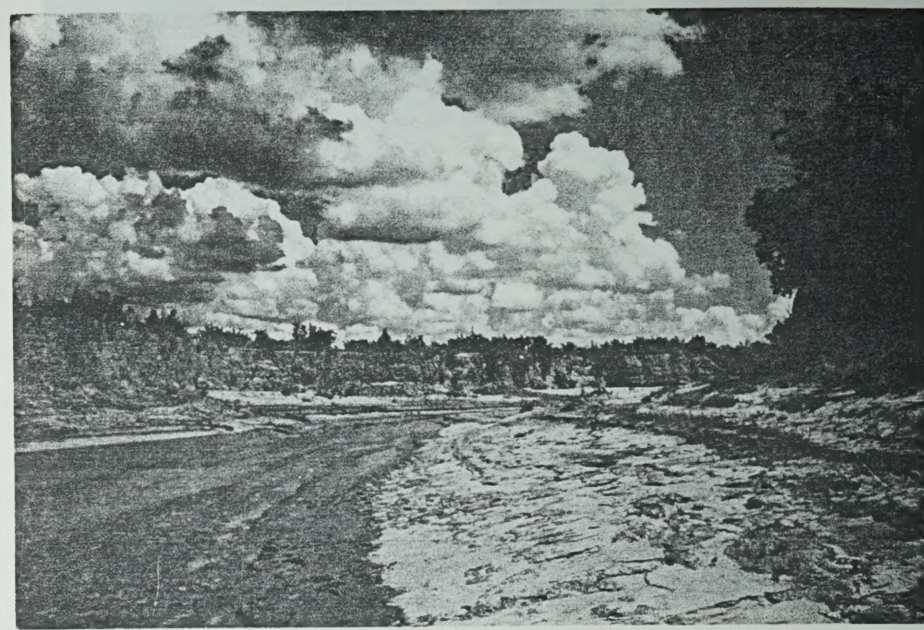
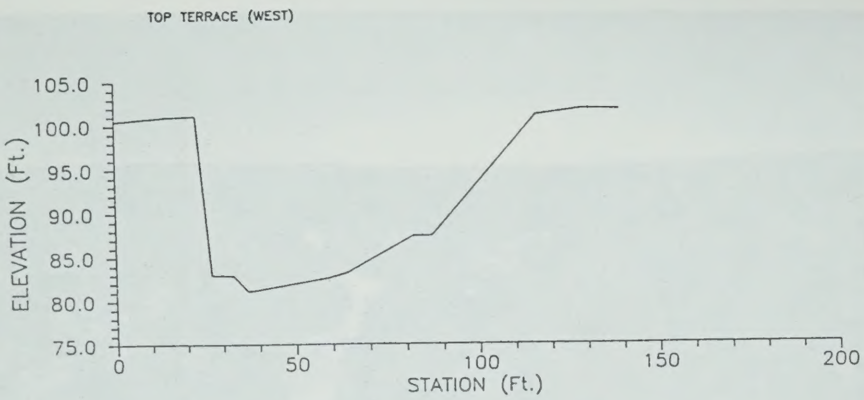


Figure 15A Cross sections and photographs, upper reaches 7 and 6, Oraibi Wash.

CROSS SECTION 5



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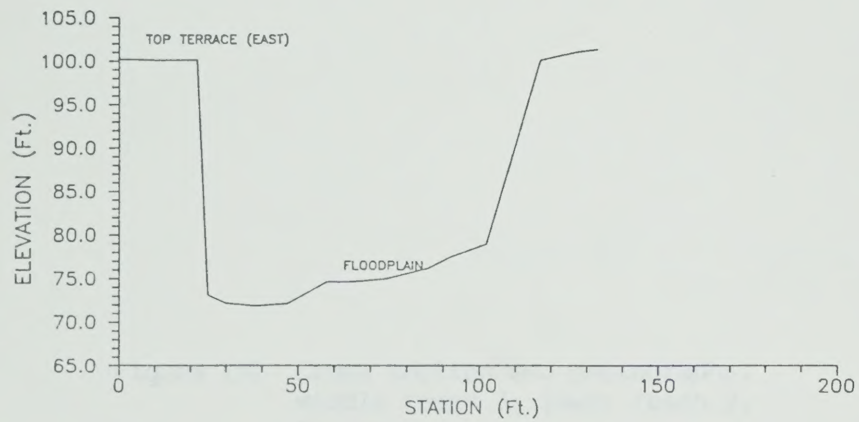

PHOTOGRAPH AT CROSS SECTION 5
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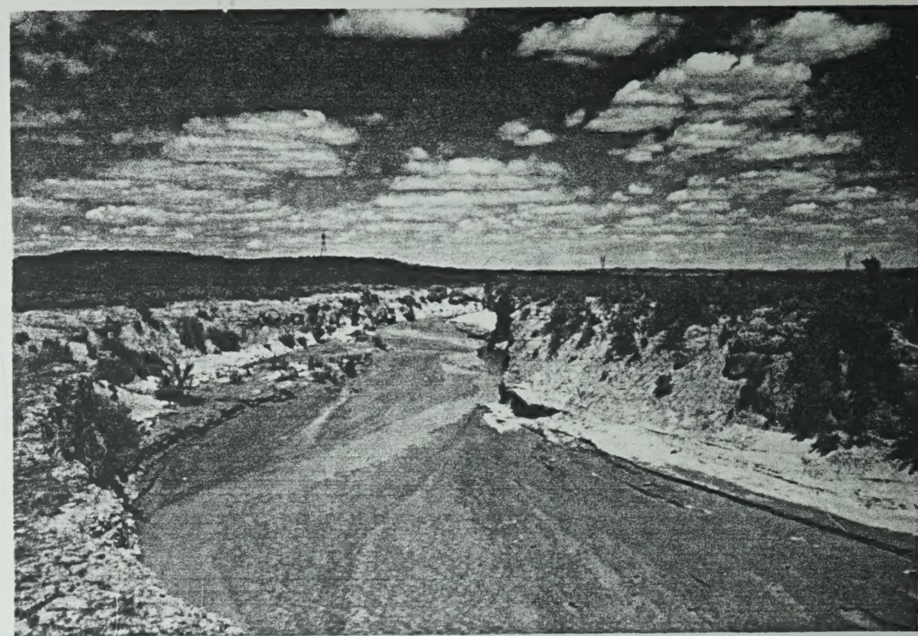
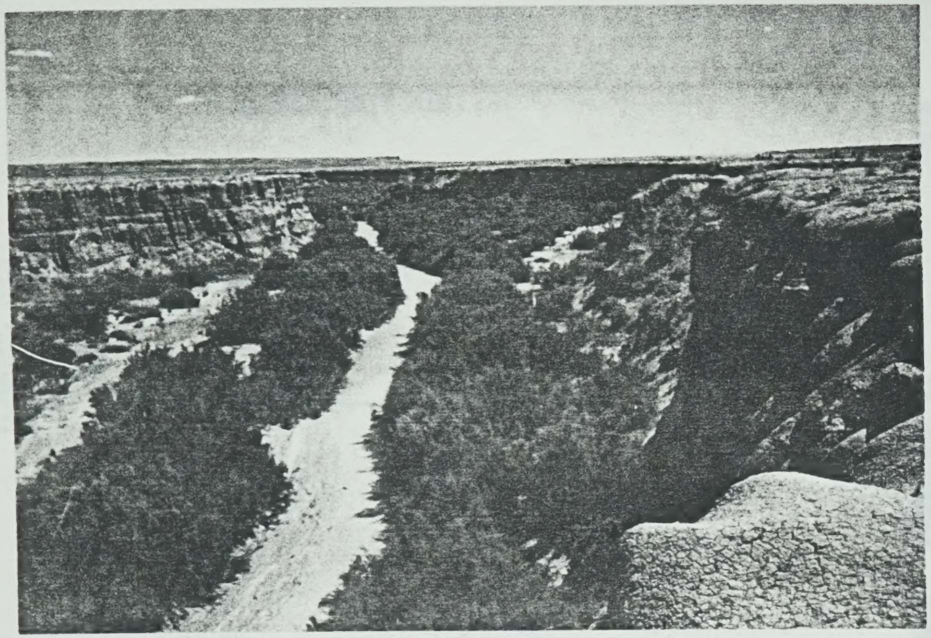
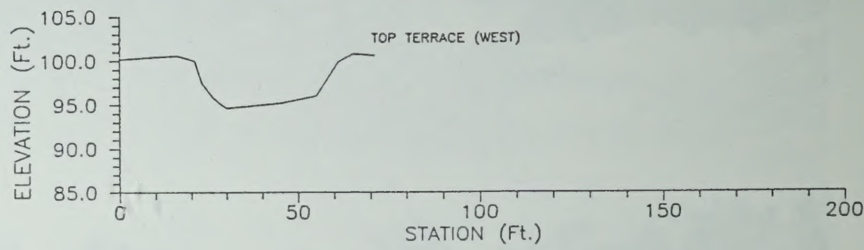


Figure 15B Cross sections and photograph, upper reach 5; middle reach 4, Oraibi Wash.

PHOTOGRAPH AT REACH 3
VIEW DOWNSTREAM



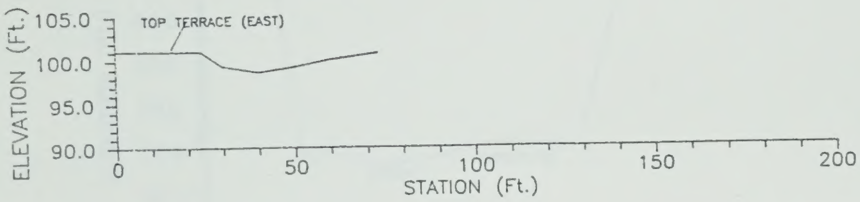
CROSS SECTION 2



PHOTOGRAPH AT CROSS SECTION 2
VIEW UPSTREAM

Figure 15C Cross section and photographs, middle reach 3; lower reach 2, Oraibi Wash.

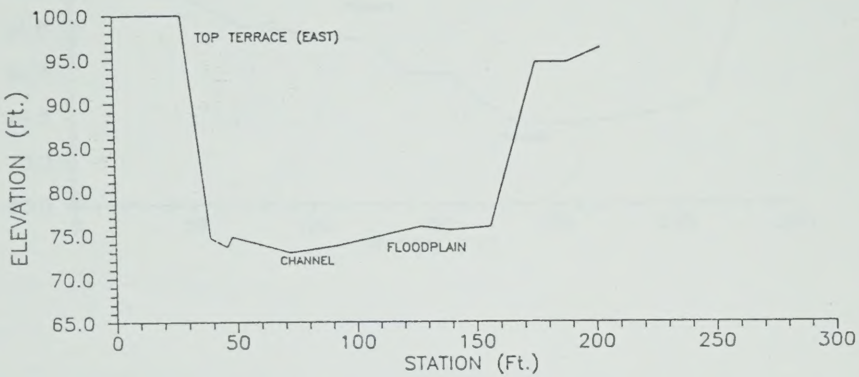
CROSS SECTION 1



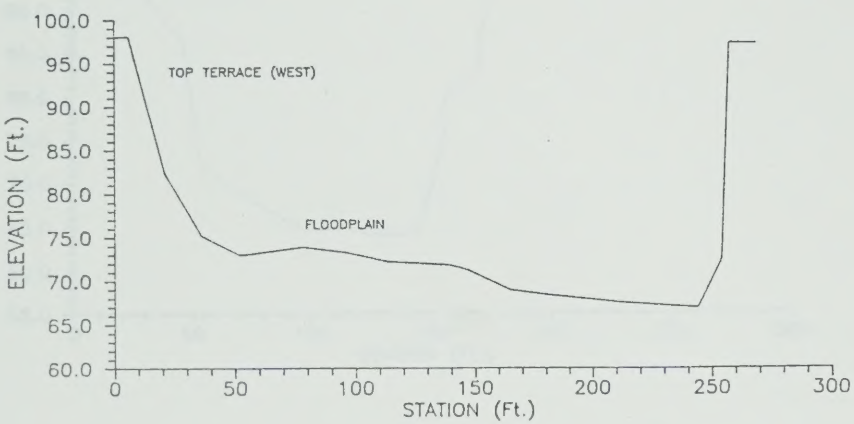
PHOTOGRAPH AT CROSS SECTION 1
VIEW DOWNSTREAM

Figure 15D Cross section and photograph, lower reach of Oraibi Wash.

CROSS SECTION 14



CROSS SECTION 13



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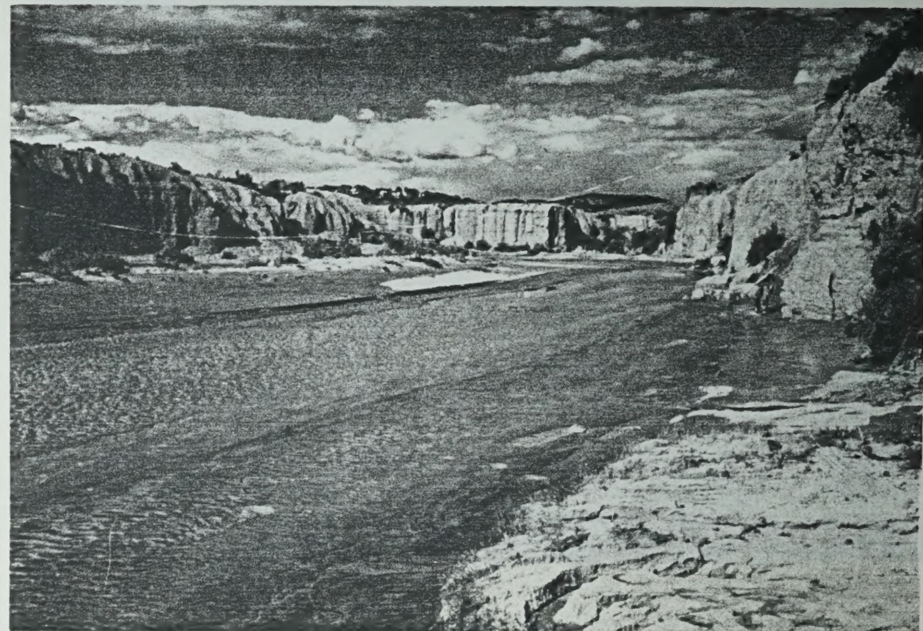
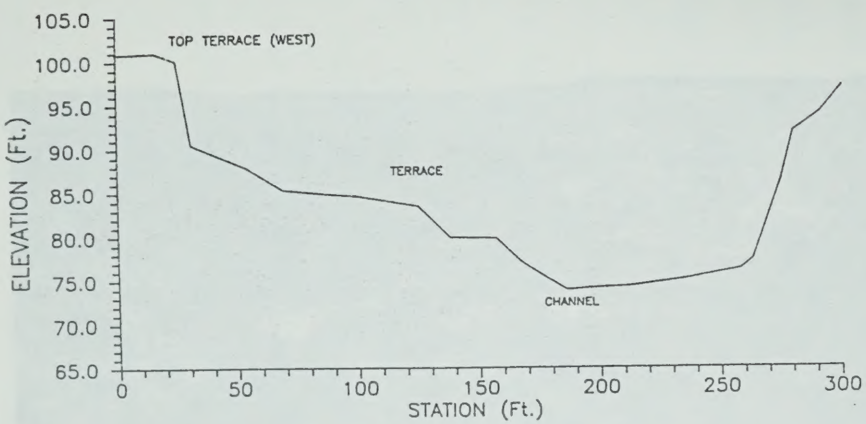
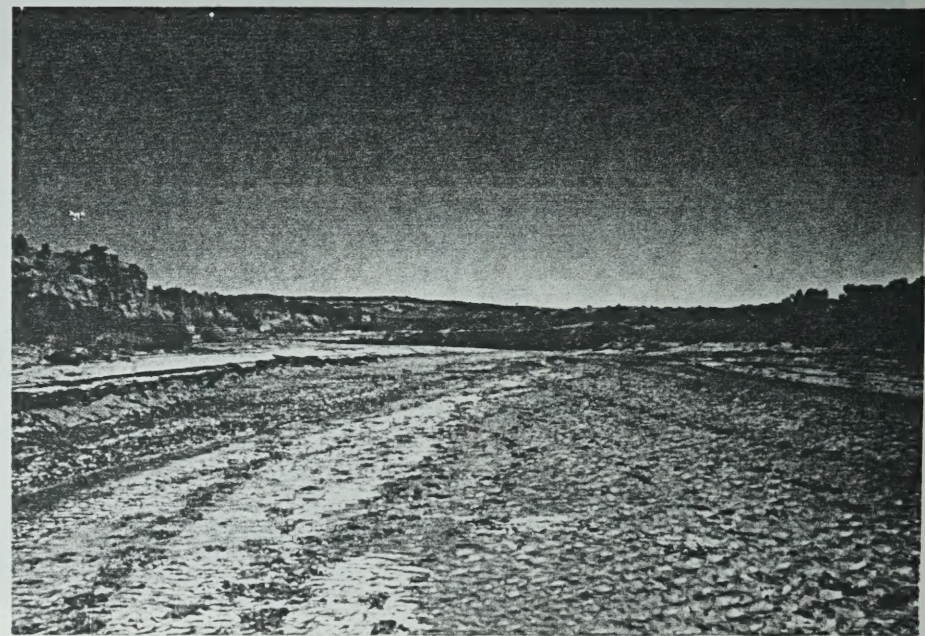


Figure 16A Cross sections and photograph, upper reaches of Dinnebito, Wash.

CROSS SECTION 12



PHOTOGRAPH AT CROSS SECTION 12
VIEW UPSTREAM



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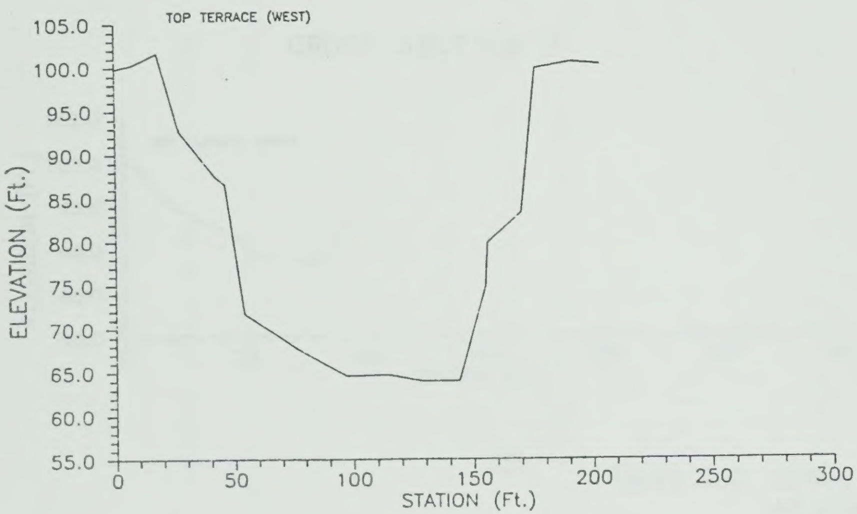
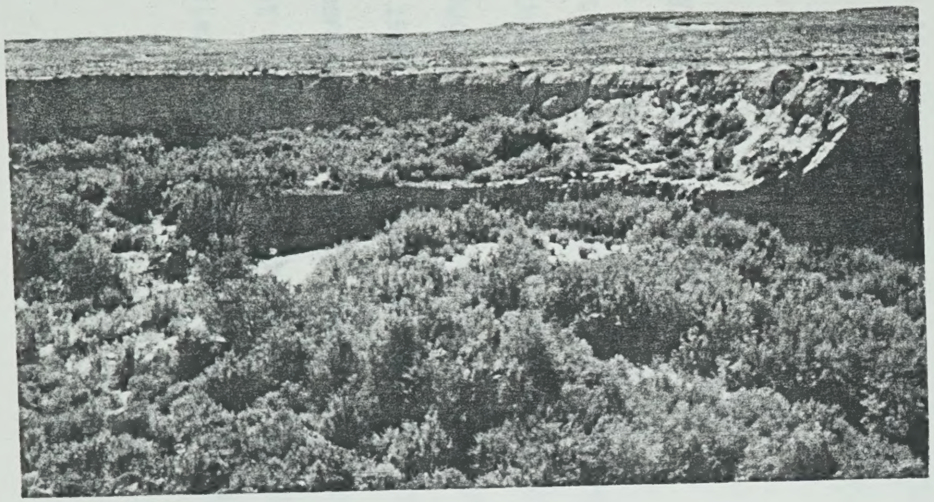
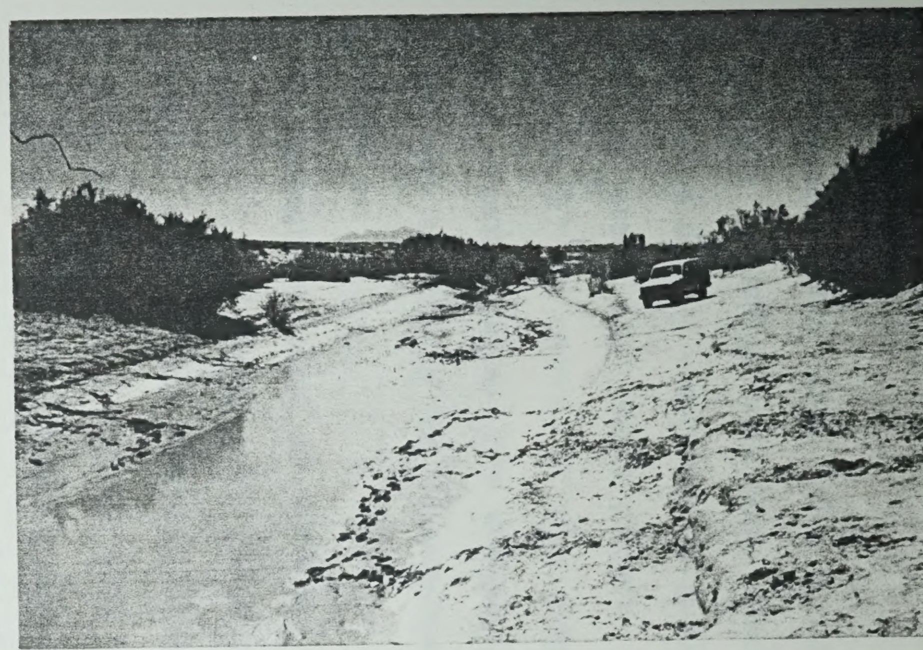


Figure 16B Cross sections and photograph, upper reach 12, middle reach 11, Dinnebito Wash.

PHOTOGRAPH AT REACH 10
VIEW DOWNSTREAM



PHOTOGRAPH AT CROSS SECTION 9
VIEW DOWNSTREAM



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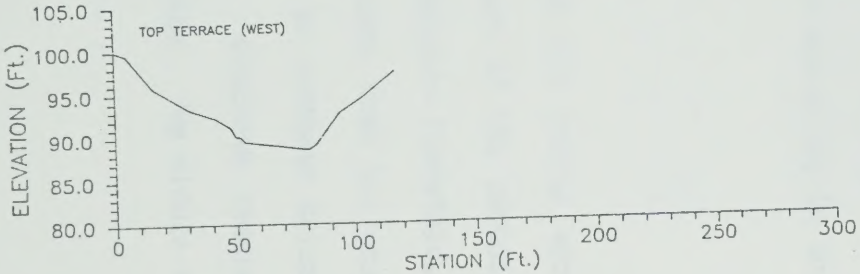

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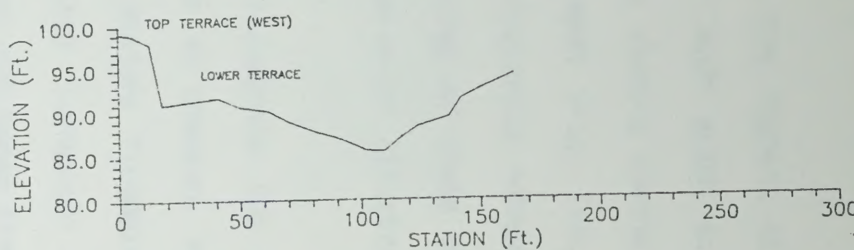


Figure 16C Cross sections and photographs, middle reach 10, lower reaches 9 and 8, Dinnebito Wash.

Lower reaches (Figs. 15C, D; 16C) represent the highest stage of maturity in arroyo evolution, characterized by high width to depth ratios, a densely vegetated floodplain with gently sloping channel banks and no steep outer walls present. In Oraibi Wash (Fig. 15D, cross section 1) the channel at this stage was morphologically nothing more than a gentle swale. The changes in the morphology of these channels are very similar to the incised-channel evolution model illustrated by Figure 14.

Photographs taken at different times also illustrate the channel changes. For example, the Little Colorado River at Cameron, Arizona, changed from a broad braided stream with an immature floodplain, in 1914, to a confined channel with a well vegetated floodplain in 1987 (Fig. 17). Figures 18A and B show similar changes for Kanab Creek, and Figure 19 illustrates how rapid the transformation can be with the change in the Puerco River at Gallup, New Mexico occurring in only ten years.

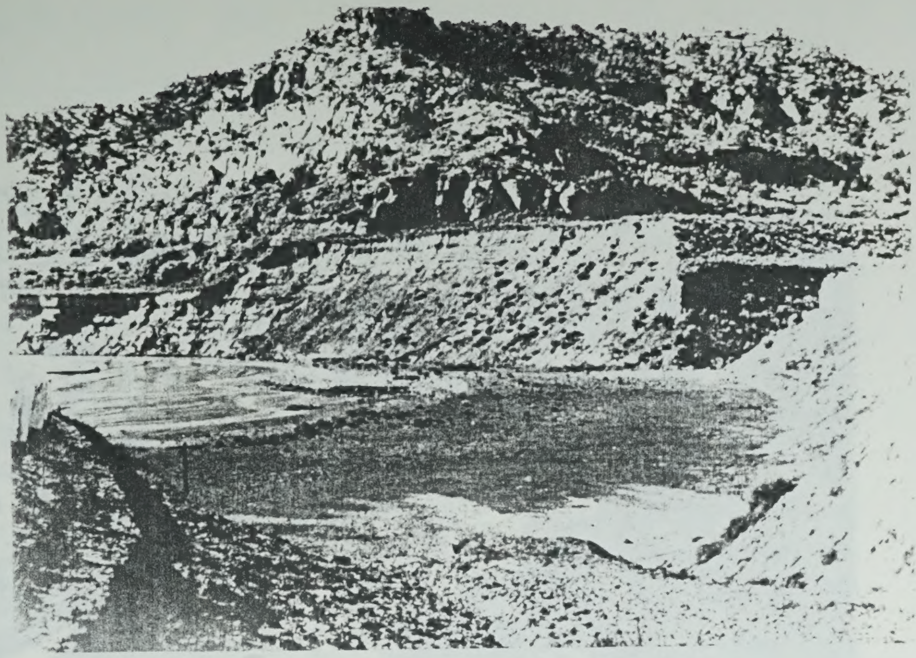
Summary and Conclusions:

Historical photographs, cross-sectional data and verbal accounts, show that the arroyos, that degraded at the turn of the century have been aggrading and forming well-vegetated floodplains (Hereford, 1984; Graf, 1987). Aggradation and revegetation proceeds from the mouths of the channels upstream. In the arroyos studied in northern Arizona, at present there are three morphologic reaches. Upstream reaches are characterized by braided actively-widening channels. The middle reaches

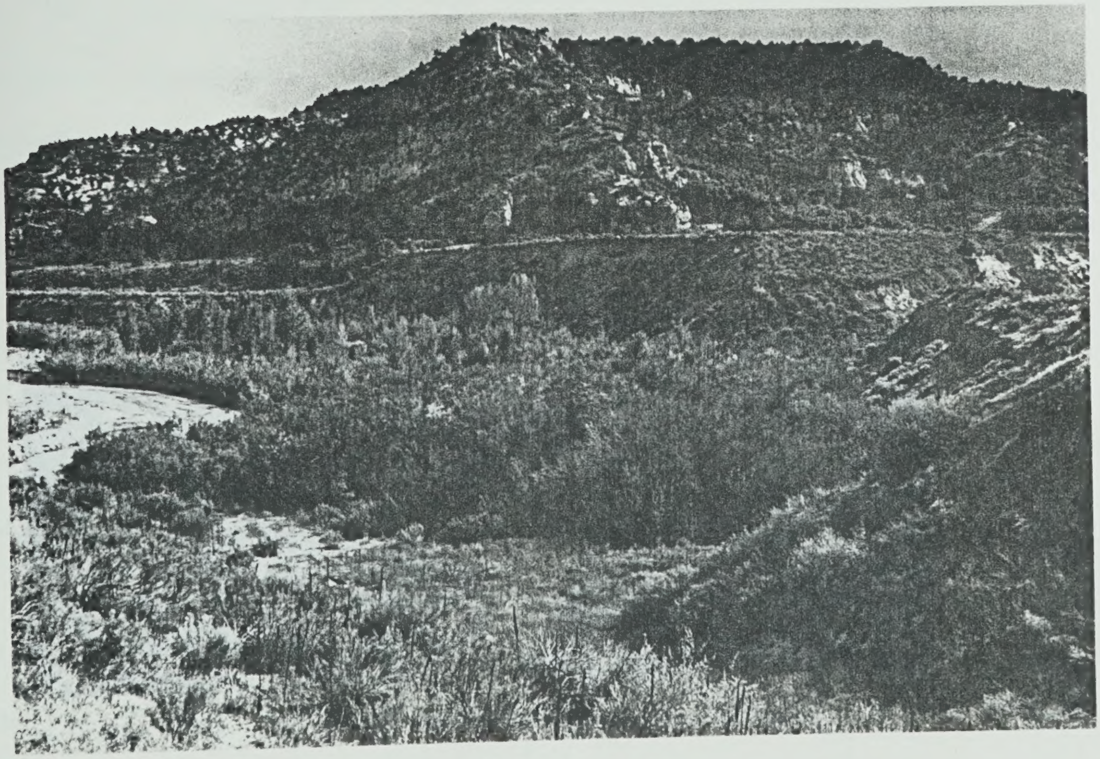
A.

B.

Figure 17 Photographs of the Little Colorado River at Cameron, AZ. A) 1914, H.E. Gregory No. 279 in U.S. Geological Survey Photographic Library, Denver, Colorado. B) 1987, R. Hereford, U.S. Geological Survey, Flagstaff, AZ. Note rock shown in both photographs at lower left center.



A.



B.

Figure 18 Photographs of the Kanab Creek at Tiny Canyon, Utah. A) 1937, H.E. Gregory No. 950 in U.S. Geological Survey Photographic Library, Denver, Colorado. B) 1987.

A

B

Figure 18. Photographs of the Kanab Creek at Tiny Canyon, Utah: (a) 1925, H.E. Gregory no. 584 in U.S. Geological Survey Photographic Library, Denver, Colorado. (b) 1987.

A.

B.

Figure 19 Photographs of the Puerco River near Gallup, New Mexico. A) 1977, Photo by Maurice Cooley, U.S. Geological Survey, Cheyenne, Wyoming. B) 1987.

Figure 15. Photographs of the Puerco River near Gallup, New Mexico. A) 1979, Photo by [illegible], U.S. Geological Survey, Cheyenne, Wyoming. B) 1980.

are highly sinuous deep arroyos with well developed point bars and floodplains supporting a dense vegetation. Lower reaches have gently sloping banks with a channel that can be almost completely filled.

The arroyos that incised deeply in the later part of the 19th century followed an evolutionary pattern that is similar to that documented for channelized streams in the Southeast and other arroyos. As channel evolution progressed, sediment production due to incision and bank erosion decreased, and the storage of sediment in floodplains increased. This combination significantly decreased the quantity of sediment delivered to the main streams. It seems probable that the sediment and salt load changes in the Colorado River and its major tributaries can be explained by arroyo evolution.

The hypothesis that evolution of arroyos may largely explain the decrease of sediment and salt loads is supported by other field and experimental evidence. For example the Rio Puerco a major tributary to Rio Grande near Bernado, N.M. has a history of arroyo cutting similar to the channels discussed earlier. The suspended-sediment load for Rio Puerco (Fig. 20) has decreased in the same manner as the Colorado River basin streams (Fig. 6) since 1947. Bryan and Post (1927) calculated that between 1887 and 1928, 395,000 acre-feet of sediment was transported out of the Rio Puerco valley. In 42 years an average of 9,400 acre-feet per year or 33,000,000 tons per year of sediment left the valley, but during the period 1948-1968 only 6,000,000 tons left the valley. There is deposition and floodplain formation in the Rio Puerco arroyo, which provides evidence of a major decrease of sediment production, as channel evolution progresses.

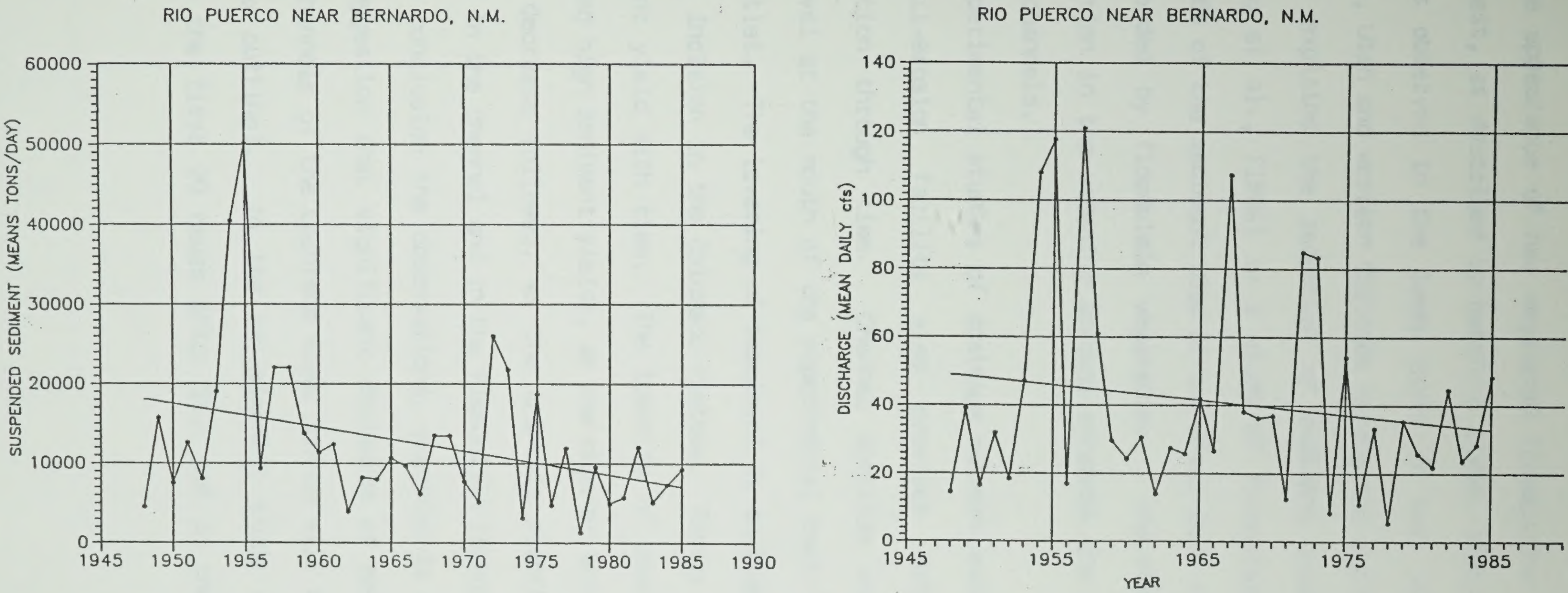


Figure 20 Suspended-sediment loads and discharge, Rio Puerco near Bernardo, N.M.

The appearance of new vegetated floodplains in the valleys of the Southwest, as described by Hereford (1984, 1986) and Graf (1983, 1985) and as observed in the lower parts of most valleys in Arizona, New Mexico, Utah and western Colorado during the aerial reconnaissance, also partly explains the reduction of sediment loads in the main river. Walling et al., (1986) in a study of floodplain deposition concluded that 28% of the sediment load of the River Culm is deposited as the flow is impeded by floodplain vegetation. Therefore, the appearance of vegetation in the widening arroyos enhances the storage of sediment in these channels.

Experimental studies of drainage network evolution in a 10m by 15m rainfall-erosion facility also provides information on sediment production through time. Channel incision was induced by lowering baselevel at the mouth of the experimental basin by removing a board at the outlet. The lowering of baselevel is analogous to the beginning of arroyo incision in the Colorado Plateau. Figure 21 shows the change of sediment yield with time. The lowering of baselevel (arroyo cutting) produced high sediment yields, as the channel incised and widened, but a rapid decrease followed, as the channels stabilized and sediment was stored in the channel and in the floodplain (Schumm, et al., 1987).

In conclusion the observations, experiments and field data confirm the suggestion that significant decreases of sediment delivery to the main channels of the Colorado River system will follow channel incision (arroyo cutting). In the experimental study this decrease occurred during the first 20 hours (Fig. 21), but in the Colorado River basin

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Experimental studies of drainage network evolution in a 15m by 15m rainfall-erosion facility also provides information on sediment production through time. Channel incision was induced by lowering baselevel at the mouth of the experimental basin by removing a board at the outlet. The lowering of baselevel is analogous to the beginning of arroyo incision in the Colorado Plateau. Figure 21 shows the change of sediment yield with time. The lowering of baselevel (arroyo cutting) produced high sediment yields, as the channel incised and widened, but a rapid decrease followed, as the channels stabilized and sediment was stored in the channel and on the floodplain (Parker, et al., 1987).

In conclusion the observations, experiments and field data confirm the suggestion that significant decreases of sediment delivery to the main channels of the Colorado River system will follow channel incision (arroyo cutting). In the experimental study this decrease occurred during the first 20 hours (Fig. 21), but, in the Colorado River basin,

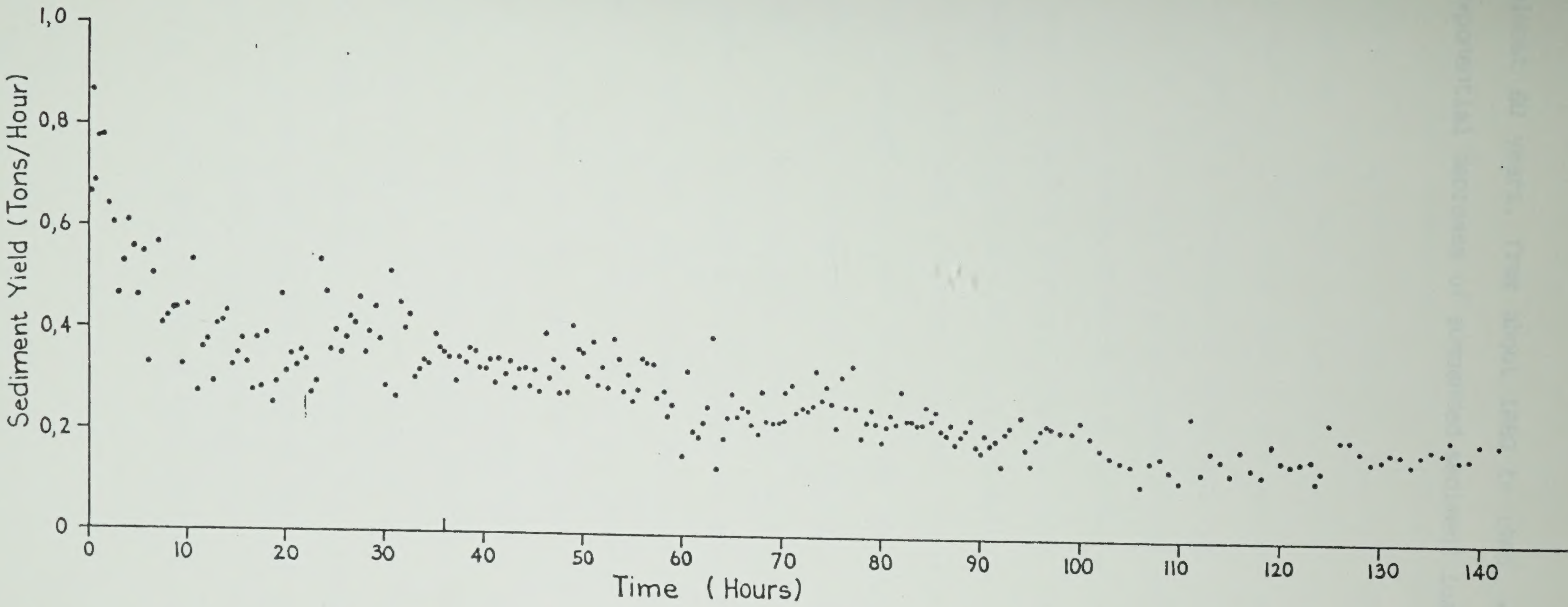

Figure 21 Sediment yield variations during experimental drainage basin evolution (from Parker, 1976).

almost 60 years, from about 1880 to 1940, was required for a similar exponential decrease of suspended-sediment load.

5) CONCLUSIONS AND APPLICATIONS

The main objectives of the Phase I research were to determine if there is a decrease of sediment and salt loads in the upper Colorado River and its major tributaries, and if such a decrease exists, to explain it. The data show a decrease in both suspended-sediment and salt loads for the Colorado River and most of its main tributaries. In addition, the change is progressive rather than abrupt.

Previous explanations for the change of sediment load based upon a change of sediment samplers (Thompson 1982, 1984a,b) should be rejected. Explanations based on climatic and hydrologic trends (Thomas, 1963) also are insufficient, although hydrologic fluctuations cause variability in both sediment and salt loads. The decreased grazing intensity and numerous soil conservation works (Hadley, 1974) undoubtedly affected local areas beneficially, but the magnitude of the impact on total sediment and salt production cannot be determined. Nevertheless, it is not probable that the decreases that have been identified are totally the result of human activities in the drainage basin.

Field work carried out by Graf (1987) in Utah and Hereford (1984, 1986) in Arizona, as well as both survey and aerial reconnaissance during this Phase I effort, reveal that substantial amounts of sediment are being stored in the lower parts of many incised channels. Not only does sediment storage in channels and floodplains reduce downstream sediment loads, but the evolution of the incised channels proceeds to a condition of minimal sediment production. The lower portions of the arroyos are not only producing less sediment, but they are also storing

sediment that is produced upstream. This appears to be the main explanation for decreased sediment loads in the Colorado River.

The decreased salt loads can be related to arroyo evolution and to reduced sediment loads because salt production is closely related to sediment production on the Mancos Shale (Nezafati, 1981; Schumm and Gregory, 1986, p. 149). Although salts are probably not stored in the recently-deposited alluvium in large quantities, the growth of salt cedar on the alluvium may store salt in the biomass. In addition, the recent deposits will bury saline bedrock outcrops both in the channel and at the base of valley walls and, in general, the filling in of numerous valleys with sediment should reduce the salt contribution from diffuse sources, which produce almost 50% of the salt load.

The decreasing suspended-sediment and dissolved-solid loads in the Colorado River basin are at least in part a result of incised-channel (arroyo) evolution (Fig. 14). However, the decrease of sediment yield may not continue without interruption. Experimental studies, in fact, showed a complex response of the fluvial system, during which the channel following initial incision aggraded and incised again, as the system hunted for a new condition of equilibrium (Fig. 22). By lowering baselevel, the system was rejuvenated (Fig. 22B). Incision occurred immediately at the basin mouth, and it migrated rapidly upstream. As incision progressed, more sediment was delivered downstream, and this caused the downstream reaches to aggrade (Fig. 22C). The channel responded by braiding. As the system approached equilibrium (Fig. 22D), renewed incision in the downstream reaches formed a low terrace.

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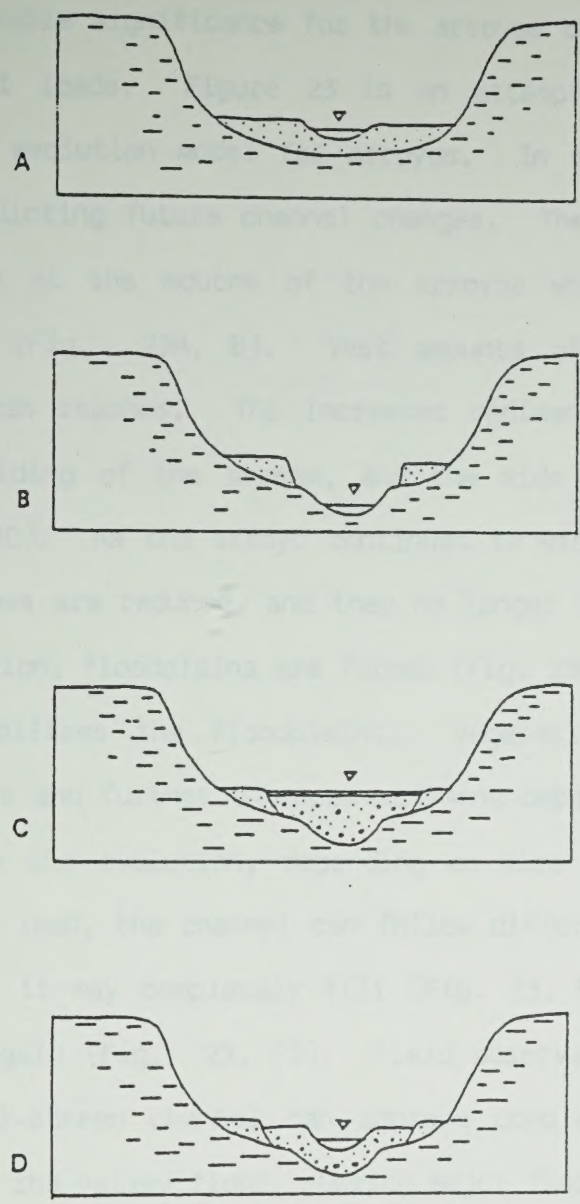

Figure 22 Complex response of an experimental drainage basin (from Schumm and Parker, 1973).

Figure 28. Complex response of an experimental drainage basin (from Schumm and Parker, 1973).

The complex response observed during experimentation has considerable significance for the arroyos of the Southwest and sediment and salt loads. Figure 23 is an attempt to illustrate the incised channel evolution model for arroyos. In addition, an attempt is made for predicting future channel changes. The first step in the model is incision at the mouths of the arroyos which migrates upstream as a headcut (Fig. 23A, B). Vast amounts of sediment are delivered to downstream reaches. The increased sediment supply causes aggradation and braiding of the stream, and the side walls of the arroyos widen (Fig. 23C). As the arroyo continues to widen, a stage is reached when peak flows are reduced, and they no longer impinge on the arroyo walls. In addition, floodplains are formed (Fig. 23D), and vegetation colonizes and stabilizes the floodplains. Vegetation increases the hydraulic roughness and further enhances sediment deposition (Fig. 23E). At this stage in the evolution, depending on size of the channel and type of sediment load, the channel can follow different modes of behavior. For example, it may completely fill (Fig. 23, F1), widen (Fig. 23, F2) or incise again (Fig. 23, F3). Field observations indicate that a small ephemeral-stream channel can aggrade completely leaving only a small swale on the valley floor. During major floods the water spreads widely over the valley floor (Fig. 23A, F1). However, larger drainage areas will normally maintain a channel, the character of which depends largely on type of sediment load. Fine sediments produce a narrow deep channel in contrast to the wide and shallow channel associated with high sand loads. As the complex-response model indicates, renewed instability can

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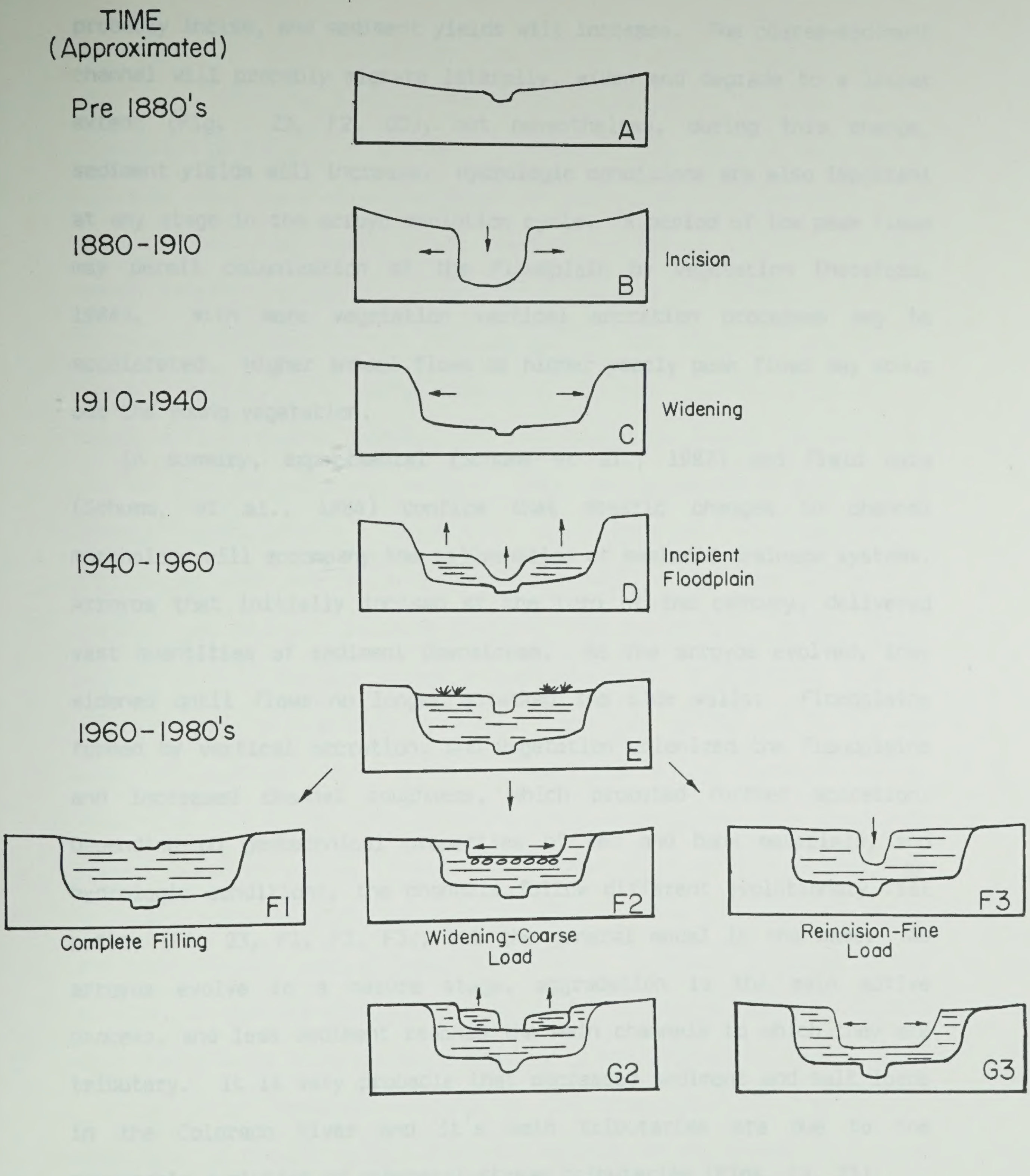

Figure 23 Model of arroyo evolution.

follow aggradation (Fig. 23F3, G3), and the fine-sediment channel will probably incise, and sediment yields will increase. The coarse-sediment channel will probably migrate laterally, widen and degrade to a lesser extent (Fig. 23, F2, G2), but nevertheless, during this change, sediment yields will increase. Hydrologic conditions are also important at any stage in the arroyo evolution cycle. A period of low peak flows may permit colonization of the floodplain by vegetation (Hereford, 1984). With more vegetation vertical accretion processes may be accelerated. Higher annual flows or higher yearly peak flows may scour out the young vegetation.

In summary, experimental (Schumm et al., 1987) and field data (Schumm, et al., 1984) confirm that drastic changes in channel morphology will accompany the rejuvenation of semiarid drainage systems. Arroyos that initially incised at the turn of the century, delivered vast quantities of sediment downstream. As the arroyos evolved, they widened until flows no longer attacked the side walls. Floodplains formed by vertical accretion, and vegetation colonized the floodplains and increased channel roughness, which promoted further accretion. Depending on geotechnical properties of bed and bank materials, and hydrologic conditions, the channels follow different evolutionary fill paths, (Fig 23, F1, F2, F3), but the general model is the same. As arroyos evolve to a mature stage, aggradation is the main active process, and less sediment reaches the main channels to which they are tributary. It is very probable that decreased sediment and salt loads in the Colorado River and it's main tributaries are due to the geomorphic evolution of ephemeral-stream tributaries (Figs. 14, 23).

Applications and Phase II Plans

Studies in small watersheds and the experimental study (Fig. 21) show that, although sediment loads are expected to decline, as the channels stabilize and sediment is stored, the complex response of channels that have been subjected to major incision indicates that continued evolution toward final stability cannot be assumed. In most cases, renewed erosion will flush stored sediment, and sediment and salt loads will increase again. This may be the most important aspect of a Phase II effort. The identification of alluvial deposits that will be eroded with increased sediment and salt loads, as stored sediments are flushed from the tributary valleys. This can, of course be prevented if channel stabilization techniques are employed. Grade-control structures, when placed at critical sites will prevent renewed channel incision and maintain sediment storage. The evolutionary scheme (Figs. 14, 23) used to explain arroyo evolution and its relation to sediment and salt loads is a geomorphic model. Therefore, geomorphic insight may also be important in determining the location of erosion control structures in a gully. For instance, a structure placed at a nickpoint, where erosion is actively creating a headcut, will be most effective in retarding gully erosion. Heede (1970, 1975) points out that continuous and discontinuous gullies require different treatment in terms of the location of control structures. Certainly structures are not required where the channel is in an aggradational or healing mode.

Time is an important variable in the development of a gully and, therefore, it should be an important variable in any scheme to curtail

arroyo erosion and to reduce sediment and salt loads. Figure 24 is a conceptual diagram that shows the change in sediment yield and active channel (gully) drainage density (length of gullies per unit area) with time. In a drainage basin that has been rejuvenated and in which the drainage network is incising and gullys are developing sediment production will increase, as the length of incising channels increase (Fig. 24, time 1 to 4). However, at time 4 maximum channel headward growth has occurred, and the channels begin to stabilize between time 4 and 7, when there is an increase in the length of channels that are relatively stable (decrease of active channel drainage density), and sediment production decreases. After time 7 the drainage basin has essentially stabilized. By understanding this cycle of channel incision and gullying from relative stability to renewed stability it is possible to select times in the cycle when land management and channel and gully control practices will be most effective. For example, gullies just initiating (times 1 or 2) and gullies almost stabilized (times 6, 7 or 8) will be the most easily controlled by artificial means. The efforts at times 1 and 2 will be most effective in preventing erosion whereas efforts at times 6 and 8 will have little effect, as the channels are stabilizing naturally. At time 4 control will be difficult and expensive. Therefore, the various stages of incised channel evolution should be determined for Southwestern channels. Also, if the causes of gully development can be determined then a program of preventive conservation may be possible, which is the most efficient way to approach the incised-channel erosion problem.

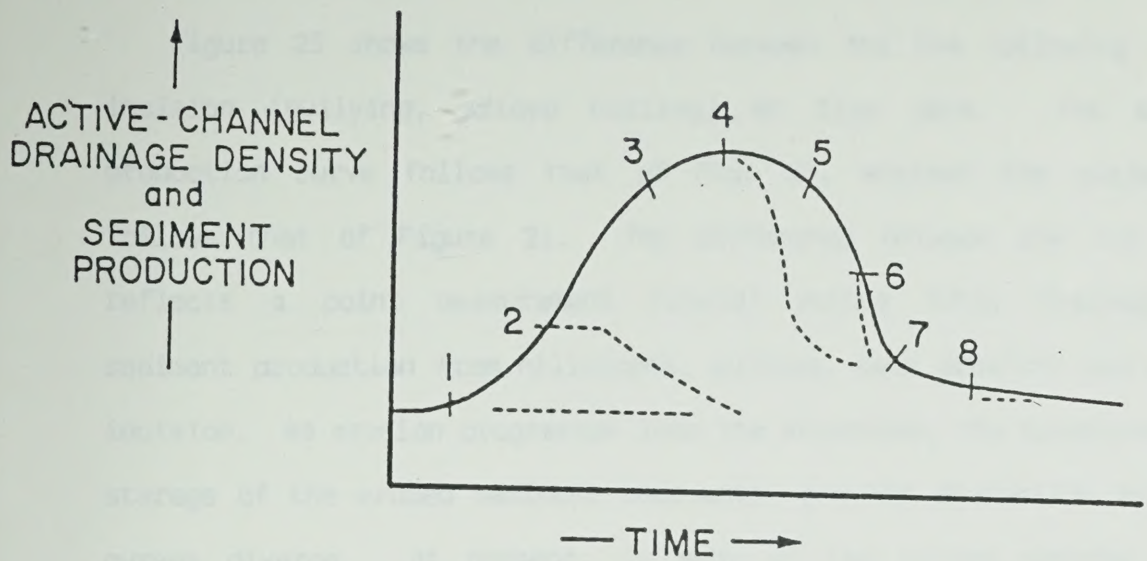

Figure 24 Hypothetical change of sediment production and active channel (gully) drainage density with time. Dashed lines indicate effect of gully-control structures at various times during channel evolution (from Schumm, 1985).

Geomorphic landform mapping, identification of geomorphic thresholds, and analysis of landform evolution will provide valuable information that can be used to assist in the resolution of the problems of sediment and salt production and sediment and salt yields in the upper Colorado River basin. It is important to distinguish between production and yield. Sediment production is the quantity of sediment eroded and mobilized in a fluvial system, whereas sediment yield is the quantity of sediment leaving the system or passing a measuring station (Figs. 5, 6, 21).

Figure 25 shows the difference between the two following channel incision (gullying, arroyo cutting) at time zero. The sediment production curve follows that of Fig. 24, whereas the yield curve follows that of Figure 21. The difference between the two curves reflects a point measurement (yield) versus total drainage-basin sediment production from hillslopes, gullies, bank erosion, and channel incision. As erosion progresses into the watershed, the opportunity for storage of the eroded sediment increases, and the production and yield curves diverge. At present, in many of the arroyo systems in the Colorado Plateau, sediment yield is decreasing, but upstream production is still very high or perhaps increasing, as main stream incision continues to rejuvenate tributary channels.

This regional picture of drainage basin response can be used to develop new methods of sediment and salt control for the Colorado River basin and other semiarid drainage basins. Even if further decrease of sediment and salt loads cannot be achieved, an increase to the former

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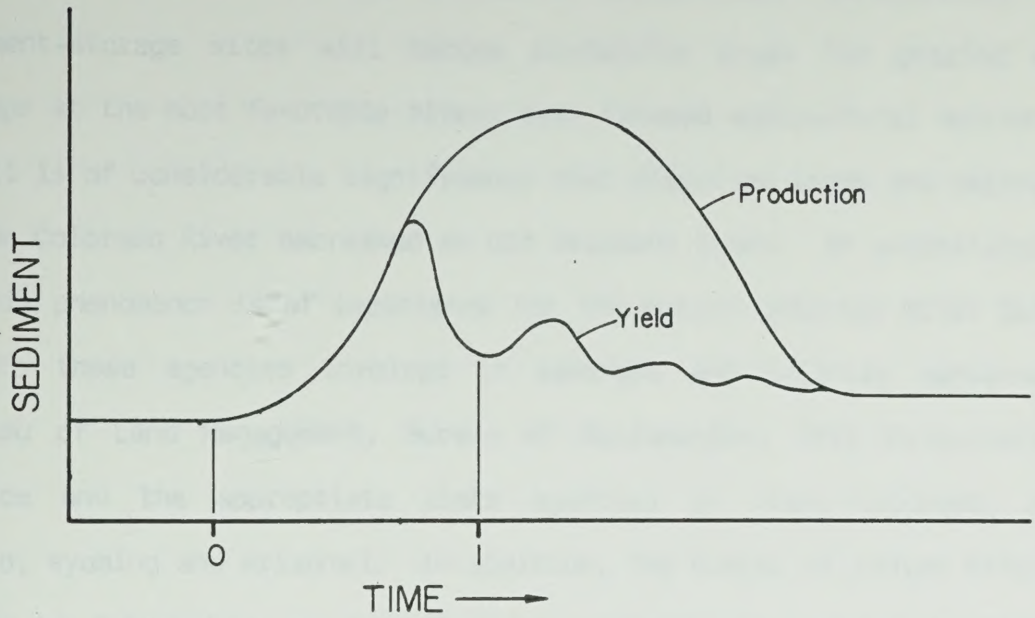

Figure 25 Comparison of sediment yield and sediment production changes with time.

high levels of sediment and salt production can be prevented if the thrust of conservation techniques can be changed from upland control to the control of sediment storage sites in valleys.

The contribution of this Phase I study and a Phase II research to the economy and benefit to the nation will lie in much more effective programs of sediment and salt control at lesser cost. In addition, the sediment-storage sites will become productive areas for grazing or, perhaps at the most favorable sites, even renewed agricultural activity.

It is of considerable significance that dissolved loads and salinity of the Colorado River decreased as did sediment loads. An understanding of this phenomenon is of importance for the entire Colorado River basin and to those agencies involved in sediment and salinity management (Bureau of Land Management, Bureau of Reclamation, Soil Conservation Service and the appropriate state agencies in Utah, Colorado, New Mexico, Wyoming and Arizona). In addition, the Bureau of Indian Affairs should be interested, as many incised channels are located on tribal lands. Because of hazards associated with unstable channels and high sediment loads the results should also be of value to U.S. Army Corps of Engineers (river stabilization), Nuclear Regulatory Commission, Environmental Protection Agency (stability of hazardous waste sites and uranium tailings sites), Office of Surface Mining (permanence of mined-land reclamation), Federal and State highway departments (highway and bridge stability.

It is anticipated that Phase II research will involve a reconnaissance of major incised channels in Wyoming, Utah, Arizona and

western Colorado and western New Mexico in order to determine if the channel adjustments are occurring generally throughout the Colorado River basin. Then detailed comparisons will be made of the evolutionary development of channels that drain areas of different rock types, and samples of the sediment will be obtained to determine if salts are being stored in the recently deposited sediment. In addition, selected valley reaches will be surveyed in order to determine if, because of different morphologic characteristics (e.g. valley and channel width and slope), some of the deposits are susceptible to renewed erosion. Any additional sediment load, salinity and hydrologic data that is located will be analyzed. The hydraulic character of flood events during different stages of channel evolution will be simulated in order to determine how the new flood plains affect flood peaks and sediment transport. Phase II research will provide a rigorous test of the explanation of the sediment load and salinity decrease in the upper Colorado River basin, as well as elsewhere in the western U.S. The degree to which individual channels have adjusted to the 1880's incision will be determined, and future adjustments will be predicted using techniques developed by Schumm et al. (1984) and Harvey et al. (1985). Finally, the results should provide a means of planning for land management and sediment control in southwestern U.S. It may be that emphasis needs to be shifted to the maintenance of the newly deposited floodplain and channel sediments. Perhaps a grade-control structure at the mouth of the incised channels will finally stabilize the lower reaches of these incised channels and permit further upstream deposition.

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